ENERGY ANALYSIS AND ECOLOGICAL EVALUATION OF A COASTAL POWER PLANT

By

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ENERGY ANALYSIS AND ECOLOGICAL EVALUATION OF A COASTAL POWER PLANT

By

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The energy basis and ecological interactions of a coastal power plant near Crystal River, Florida were evaluated at three hierarchical scales of study: the power plant region (powershed); the broad mosaic of coastal ecosystems interacting with the power plant; and the ecosystems of the cooling water canals at the interface between estuary and power plant. Information was developed from model studies, computer simulations, field measurements, compilations of data from project reports, maps of land use, and energy analysis.

The Crystal River powershed was supported by a diverse array of energy inputs. About 1.9 times as much energy was contributed from fossil fuels as from natural (solar-based) sources. The ratio of fossil fuels to natural energy inputs for this region was about 30% lower than the national average (2.7), indicating the region might be relatively undeveloped. However, the proportion of fossil fuels invested

in electric power generation in the powershed (0.52) was 67% higher than the national average (0.27) and 7% higher than the Florida average (0.42). Thus, there has been large investment in power plants for this region, possibly in anticipation of further economic development.

The Crystal River power plant has had substantial impact on adjacent estuarine ecosystems. Major areas of impact included entrainment mortalities inflicted on meroplankton and juvenile fish, as well as inhibition of productivity in the ecosystems receiving power plant discharges. These effects were documented and evaluated in coal equivalent (CE) energy units. The total annual cost to the estuaries and region resulting from power plant construction and operation was estimated to be 7.7×10^9 kcal CE/yr (equivalent to about $385,000/yr).

A simulation model of the estuarine ecosystems receiving thermal wastes was used to predict the effects of adding a third generating unit. A parabolic relationship between temperature and productivity, derived as a simplification of theoretically based functions, produced model behavior which closely matched field data. It was estimated that the ecological effects of a 3-unit power plant (13.8×10^9 kcal CE/yr) would be almost 80% greater than for the 2-unit plant. The costs of using technological measures to ameliorate these ecological impacts were compared to the ecological impacts themselves. The cheapest closed-cycle cooling system would cost about $\$17 \times 10^6$/yr ($350 \times 10^9$ kcal CE/yr), which was about 25 times greater than the estimated damage to the ecosystem.

The power plant's effects on stocks of estuarine organisms were evaluated in terms of equivalent amounts of primary productivity needed to support these organisms. A model was developed to do this by describing generalized functional relationships between trophic levels in an estuarine ecosystem at Crystal River. Detailed data from a salt-marsh creek ecosystem were used to evaluate stocks and energy flows in the trophic web. For example, the model indicated that a kilocalorie of mullet (*Mugil cephalus*) and jack (*Caranx hippos*) production would require 20 and 300 kilocalories, respectively, of gross productivity.

The cooling water canals were observed to be viable interface ecosystems characterized by high productivities and large standing stocks of animals. Mean levels of gross primary productivity in the canals (7.8 $O_2/m^2 \cdot$day) were 33% higher than adjacent bay ecosystems. Standing stocks of benthic animals and nekton in the canals (31.2 g organic/m^2 and 3.2 g dry/m^2, respectively) were about 4.5 and 2 (respectively) times higher than in the bays. The intake canal provided a habitat to grow certain nekton species which were impinged at the power plant intake, but overall, it served only as a channel to direct fish from outside the canal to the power plant.

INTRODUCTION

Understanding the combined systems of man and nature is a major need in studying the ecology of large scale systems. In this dissertation the ecological, economic and energy relationships of a steam electric power generating plant in a coastal zone region are investigated. Economic data, energy budgets, and maps of land use and energy density are developed to consider relationships between the availability of natural energy resources and the growth of electric power industries in a coastal zone.

Information developed by many investigators in a coordinated research project sponsored by Florida Power Corporation is synthesized using energy analysis. Effects of power plant operation on estuarine ecosystems are measured and compared in energetic terms to the cost of mitigating them with environmental technology such as cooling towers. Computer models simulating ecosystem behavior are developed and used to predict potential effects of alternative cooling water schemes on the estuary and its subsystems. Field measurements of ecosystems in the power plant canals are used to evaluate the energy interactions and ecological character of these unique systems at the interface between power plant and estuary.

Hierarchical Scales of Study

Relationships between various components of this study are depicted in Fig. 1, which shows the general chain of interactions between regional economy, power plant, canal ecosystems and estuary. From a spatial point of view, the power plant functions at several levels within its region of influence. To understand the structure of power plant systems, three hierarchical scales of size were identified for modeling. Diagrams that were highly detailed initially were aggregated and condensed until the hierarchical structure of the system clearly emerged. In this way the smallest scale models could include much detail without the study losing its holistic point of view. Since each subsystem was a component in a larger system, information gleaned from examination at one level could be effectively transferred to study at other levels (see Simon, 1965; Pattee, 1973).

Relationships between the three hierarchical levels of focus for the present study are illustrated in Fig. 2. Diagrams show the aggregated system components and interactions at each scale. The dashed lines between subsystem diagrams indicate the manner in which lower levels are nested into higher level systems. Maps of successively smaller scales paralleling the diagrams are presented to suggest two-dimensional spatial relationships.

Power Plants in the Coastal Zone

In the past century western technological societies have become critically dependent on fossil fuels which have nurtured an accelerated growth. Because of its versatility as a means of distributing energy, electricity has become an integral part of the technological system, so that presently about 27% of the fossil-fuel-based energy consumed

Figure 1. Diagram of the general chain of interactions between regional economy, power plant, canal ecosystems, and estuary. For explanation of symbols see H.T. Odum (1971).

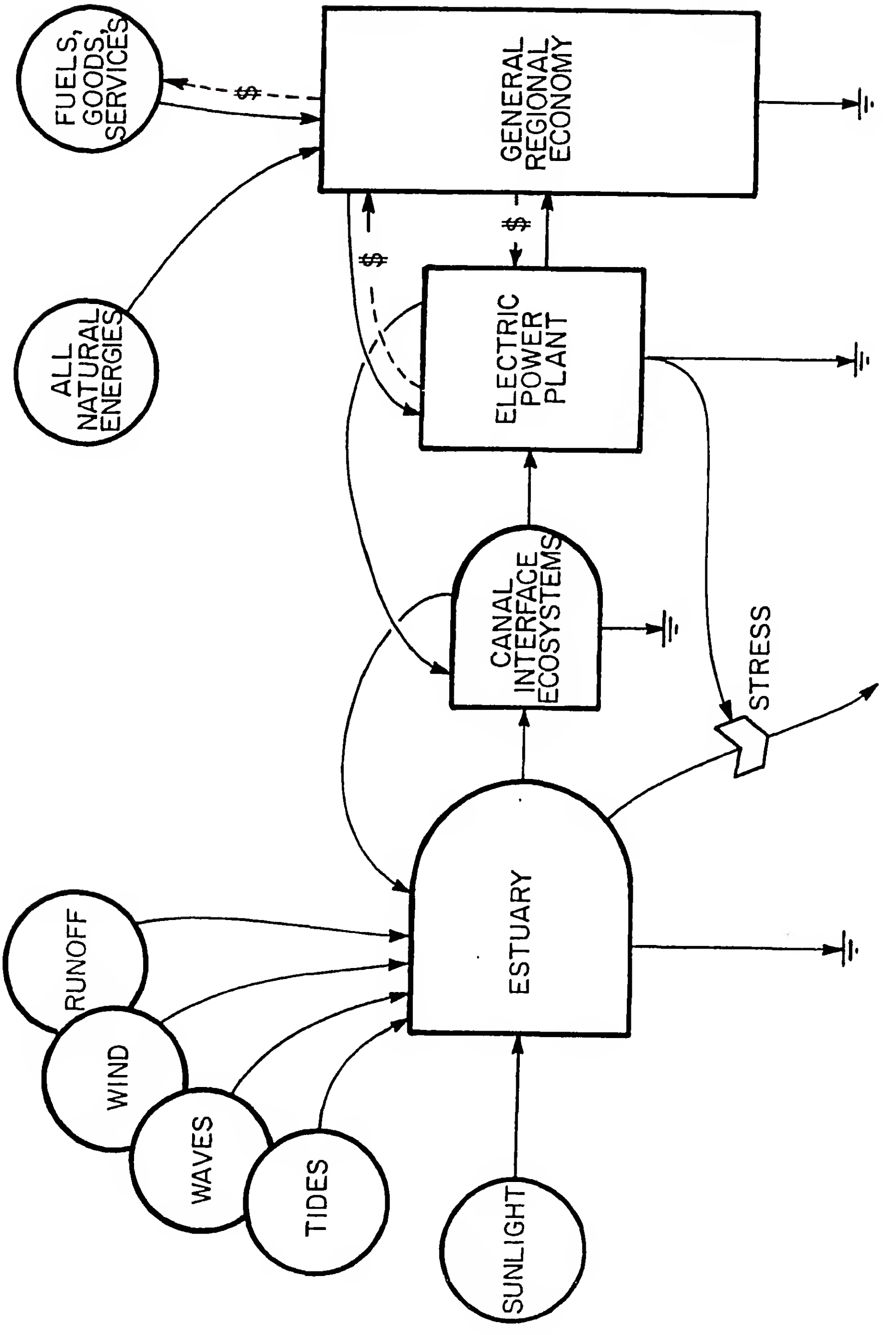
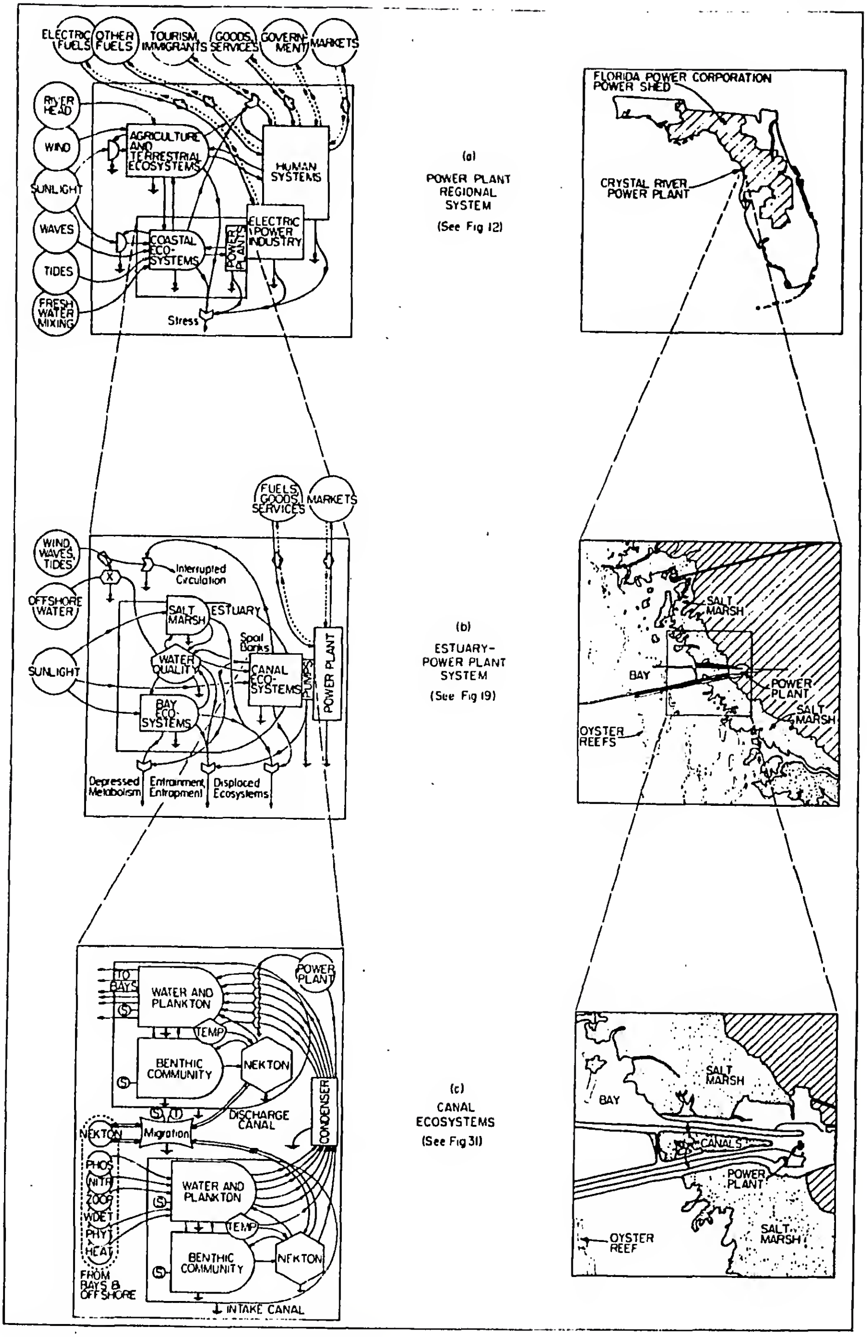

SUNLIGHT
TIDES
WAVES
WIND
RUNOFF
ESTUARY
STRESS
CANAL INTERFACE ECOSYSTEMS
ELECTRIC POWER PLANT
$
$
GENERAL REGIONAL ECONOMY
ALL NATURAL ENERGIES
FUELS, GOODS, SERVICES
$

Figure 2. Energy diagrams and maps of Crystal River Power region showing three hierarchical scales studied. For explanation of symbols see H.T. Odum (1971).



(a)
POWER PLANT
REGIONAL
SYSTEM
(See Fig 12)

(b)
ESTUARY-
POWER PLANT
SYSTEM
(See Fig 19)

(c)
CANAL
ECOSYSTEMS
(See Fig 31)

in the U.S. is involved in electric power generation (Smith, 1975). In the United States electric power production has increased some 200 fold in the last 60 yrs while population has barely doubled during the same period (Rainwater, 1968; Mihursky et al., 1970; Smith, 1975). At present, over 80% of the electricity consumed is generated by fossil fuel fired steam electric plants, and the remainder is produced by hydroelectric and nuclear plants (Federal Power Commission, 1971; Smith, 1975).

During this time of rapid growth the availability of fuels to support our complex human systems was seldom questioned, and the value of nature in providing man's life-support system was little recognized. However, the "energy crisis" of 1973 dramatically emphasized the limited nature of fossil fuel supplies and the dependence of regional economies on these energies. The ability of a regional system to make effective use of its energy resources may determine the pattern of that system which ultimately survives (Lotka, 1922; Odum, 1973).

Coastal zones that include man, like all regional systems, are supported by a compatible influx of natural and purchased energies. As fossil fuel supplies dwindle natural energy resources of the coast become even more important. The coast is a junction between land and sea; it is here that energy flows originating from inland sources (such as river waters with their kinetic and chemical energies) mix with wave and tidal energies from the ocean. The shallow aspect of estuaries tends to concentrate these energies for utilization in ecological and geological work processes.

These highly productive coastal areas, with their well-flushed waters and scenic vistas, have generally attracted dense human settlements. More than 50% of the population of the United States is located in counties bordering the oceans and Great Lakes (Ketchum, 1972). Power plants require large volumes of water for condenser cooling, and the Federal Power Commission (1971) has indicated that some 374,000 m^3/min (220,000 cfs) of cooling water would be needed in the U.S. for power plant cooling in 1975. Since coastal regions offer an abundant supply of cooling water and have attracted much of the urban development that demands electricity, power plants have been sited with increasing frequency along the coastline. At least 30% of the water pumped through steam electric power plants is coastal water (Federal Power Commission, 1971).

Estuarine ecosystems contiguous to these electric generating stations are subjected to new conditions that result from pumping of cooling water, thermal discharges and other influences associated with the power plants. After a transition period the affected ecosystems are modified or replaced in adaptation to these altered energy conditions. In planning for a compatible coupling of power plants and estuaries, it is necessary to understand the character of these new ecosystems.

Interface Ecosystems and Environmental Technology

A choice exists between developing technological systems or interface ecosystems to connect power plants and estuaries.

Interface Ecosystems

At the interface between areas of human activity and natural environments are a variety of new ecosystems, which couple the energies of nature with those of man. These ecotonal regions have unique characteristics arising from the special combination of natural and fossil fuel-based energies which drive them. Odum et al. (1977) have termed this general category of systems as "interface ecosystems." These systems channel and transform energies eminating from human processes so that they can be exploited by natural systems, and they may buffer downstream ecosystems from the stress of man's wastes. Reciprocally, the interface ecosystems can concentrate natural energies for use by man.

Some of the organisms in the ecosystems receiving these wastes are stressed and may be eliminated from the system. However, through the trial-and-error process of self-design, other species are introduced and become component parts of the interface system, adapted to tolerate and use the energies in these waste discharges. Thus, new systems, with specialized complements of biotic components and other properties intermediate between the wastes and original environment, emerge at the boundaries between man and nature. For the coastal zones of the U.S. Odum et al. (1974b) have categorized and described some of these interface ecosystems. Recently, a number of projects have been undertaken in attempts to identify and domesticate ecosystems for waste recycling and other purposes so that they could be utilized systematically to reduce environmental impact and save money (Odum et al., 1970; Ryther et al., 1972; Kuenzler et al., 1973; Valiela et al., 1975; Odum and Ewel, 1974).

Power Plant Canals as Interfaces

Large canals which carry cooling waters to and from the power stations are often associated with estuarine and coastal electric power plants. The ecological systems that develop in canals are important components at the interface between power plant and estuary. They allow the plant buildings to be set-back from the shoreline area, and may separate cooling water intake and discharge points so as to minimize recirculation. Intake canals may extend into offshore waters which are cooler in the summer, thus allowing condenser-turbine systems to be more economically designed for lower back-pressure, but such protrusions into open water can cause alterations of local hydrographic patterns. Canals may also function as channels and ports for fuel barges. Cooling water canals are generally 50-100 m wide. They are usually deeper than adjacent aquatic ecosystems, but have a larger shoreline to surface area ratio. Rip-rap or talus materials often line the periphery of the canals to prevent bank erosion, and this substrate can provide a good habitat for benthic communities. The constant flow of cooling water contributes to the metabolism of canal ecosystems, keeping them well flushed and generally well fed.

Heated effluent canals often attract nekton communities during cooler months, and are noted for excellent sport fishing (Nugent, 1970; Landry and Strawn, 1973; Moore et al., 1973; AEC, 1973a). Incurrent canals, however, channel fish to their death on the rotating screens which filter the cooling water before it flows into the plant. Extreme summer temperatures often exclude fish from the effluent canal (Nugent, 1970; Clark and Brownell, 1973; AEC, 1973a), while unexpected shut-downs of power plants in winter can cause cold-shock mortality to fish (in the canal) which would normally migrate to warmer, offshore waters in the autumn (Young, 1973; Raney, 1971; Clark and Brownell, 1973). Table 1 lists some of the major coastal power plants in the U.S. with cooling canal systems. These canals range in length from < 1 km to nearly 10 km.

Environmental Technology

In the past 50 yrs in the U.S., large sums of money and energy have been invested in waste treatment technology to alleviate some of the adverse environmental effects of human waste products. The simplest of these treatment schemes are themselves ecosystems (such as sewage lagoons) and involve only small flows of money and fossil-fuel-based energies to subsidize natural recycling processes. These interface ecosystems are often highly successful and economically sound (Bartsch and Allum, 1957). However, during the recent period of growth in the U.S., the trend has been to build more sophisticated, more expensive technological treatment plants, which substitute fossil fuel energies for the energies of nature to accelerate waste recycling. In some of these "environmental technologies" such as tertiary sewage treatment, natural nutrient materials may be virtually removed from biogeochemical cycles.

Electric power generating plants are high-energy nodes in the network of human activities. Construction and operation of power plants constitute a major energy and economic investment in a region resulting in large waste energy residuals. In planning for coastal power plants, alternatives of technological cooling should be compared

Table 1. Some major coastal and estuarine power plants in U.S. utilizing cooling water canal systems.

Name of Plant	Location	Cooling Water Flow m^3/min	Length of Canals, km	
			Intake	Discharge
Pilgrim[c]	Cape Cod Bay, Ma.	1223	---	0.4
Brayton Point[c]	Naragansett Bay, Ma.	2297	---	0.4
Millsonte[d]	Niantic Bay, Conn.	3545	---	0.5
Conn. Yankee[e]	Conn. R., Conn.	1505	---	1.9
Oyster Creek[c]	Barnegat Bay, N.J.	1632	1.1(2.4)[a]	1.0(2.4)[a]
Indian River[c]	Indian R., Del.	570	0.2	3.0
Peach Bottom[f]	Susquehanna R., Pa.	5690	---	1.4
Chalk Point[c]	Patuxet R., Md.	1894	0.5	2.4
Morgantown[g]	Potomac R., Md.	4250[b]	---	0.6
Douglas Pt.[g]	Potomac R., Md.	2400[b]	0.3	---
Yorktown[h]	York R., Va.	2700[b]	0.3	0.5
Surry[c]	James R., Va.	6360	3.2	0.8
Chesterfield[i]	James R., Va.	2776	---	0.5(6.0)[a]
Cape Fear[c]	Cape Fear, N.C.	1017	---	---

Table 1. (Continued)

Name of Plant	Location	Cooling Water Flow m^3/min	Length of Canals, km	
			Intake	Discharge
Brunswick[j]	Cape Fear, N.C.	6800	5.2	9.7
Turkey Point[k]	Biscayne Bay, Fla.	2176	0.5	6.6
Anclote[l]	Tarpon Springs, Fla.	2720	1.0	1.2
Crystal River[m]	Crystal River, Fla.	2414	5.0	2.0
Bartow[n]	St. Petersburg, Fla.	1476	0.3	0.3
P.H. Robinson[c]	Galveston Bay, Tex.	4226[b]	2.5	2.5
Cedar Bayou[o]	Galveston Bay, Tex.	2550[b]	---	9.8

[a] Numbers in parentheses indicate tidal creeks which are serving as canals.

[b] Estimates based on megawatt rating and condenser temperature rise. [c] Clark and Brownell (1973); [d] AEC (1973b); [e] AEC (1973a); [f] AEC (1972c); [g] W. Boynton (personal comm.); [h] White et al. (1976); [i] Koss et al. (1974); [j] AEC (1974); [k] Nugent (1970), prior to the construction of Unit 3; [l] Kemp (1976); [m] this study; [n] Blake et al. (1976); [o] Gilmore et al. (1975).

with the alternative of using ecosystems which develop in power plant cooling water canals as ecological interfaces. To make wise use of a region's natural resources, it may be necessary to determine what is the best mix of natural and fossil fuel energies in "interface" areas.

Questions on Roles of Coastal Power Plants

The following questions are addressed in this study.

1) What are the useful environmental planning techniques for optimizing power plant designs toward a viable regional economy?
2) What are the major effects of an existing two-unit power plant on the nearby coastal ecosystem? How can these be evaluated in energy terms for comparison?
3) What additional effects are likely to occur with the expansion of present power plant facilities to include a third generating unit?
4) What are the main characteristics of cooling water canals as interface ecosystems?
5) What are the relative trade-offs between the ecological modifications resulting from human activities and the environmental technologies which attempt to ameliorate such modifications? Is investment of capital into these environmental technologies a competitive use of energy resources?
6) Defining an "energy quality ratio" as the energy cost of transforming one energy form to another divided by the heat calories in the original energy flow, what are the relative "qualities" of natural energies supporting a coastal region?

7) What are the relative qualities of energy processed by higher trophic-level organisms? How can energy quality calculations be used as a scale to evaluate the effects of power plants on organisms?

8) What are major energy sources supporting a coastal power plant's region? How does the addition of new capital inputs to the region (in the form of cooling towers or expanded generating capacity) affect the balance between fossil fuels and natural energies therein?

Other more specific questions are also investigated.

9) What are the effects of temperature, turbidity and current on ecosystems in the discharge canal at Crystal River? How will these effects be altered when the third generating unit becomes operational?

10) Does the intake canal serve as a major habitat for nekton which are impinged on the power plant intake screens? Does the canal act to concentrate nekton from adjacent estuaries? How will this be affected by operation of the third unit?

11) Can a two-station diurnal oxygen method for measuring community metabolism be used to estimate tidally influenced, stratified coastal systems?

Before reporting results of the study of these questions, literature and unpublished reports are reviewed on environmental effects associated with coastal power plants in the U.S.

Previous Studies of Interactions Between Power Plants and Estuaries

In recent years much information has been provided, documenting and describing the effects of power plants on adjacent aquatic ecosystems, although a large portion is in contract reports. Much of the work describes the effects of elevated temperatures on the physiology and behavior of particular species, and only recently has there been a major effort to characterize power plant effects at the ecosystem level. Indices of plankton and community metabolism may best indicate the health of an ecosystem (Odum, 1967). The overall energy response of estuaries to power plant discharges can be described with productivity and respiration field measurements. In addition, several investigators (Tarzwell, 1972; Clark and Brownell, 1973) have suggested that ecological problems resulting from thermal discharges may be less significant than problems of plankton entrainment and nekton impingement at the cooling water intake. A brief review of the accessible literature on community metabolism, zooplankton entrainment and nekton impingement follows.

Power Plant Effluents and Community Metabolism

Eppley (1972) reviewed a large number of papers investigating the effects of temperature on metabolism and growth of phytoplankton in the sea and indicated that with increasing temperatures photosynthesis increased up to about 30-35°C and thereafter decreased. The effect of temperature on photosynthesis was reduced greatly under conditions of limited light and nutrients. In a review of studies at various thermal springs, Brock (1970) showed that extreme temperature inhibited the functioning of even these steady-state climax systems. Maximum algal net production occurred at slightly higher temperatures than for gross production, probably because animal grazers were excluded at the very high temperatures.

A general pattern observed for seasonal responses of photosynthesis to power plant operation in temperate climates is a wintertime stimulation of metabolic rates in discharge areas, with suppression of productivity occurring in the warmer months. Warinner and Brehmer (1966) using both carbon-14 (C-14) productivity and oxygen bottle methods described this pattern at the York River estuary in Virginia. Smith et al. (1974a), Brooks (1974) and Brooks et al. (1974) reported C-14 measurements of phytoplankton at four mid-Atlantic power plants (3 estuarine sites) and concluded that productivity was generally increased by almost half in the colder months (daily mean temperature $\leq$ 20°C), but decreased by 30-50% during the summer. Similarly, Carpenter et al. (1974a) found that C-14 productivity of discharge waters was about 75% less than controls in the summer and 35% less in the spring, but 110% greater in the winter and 15% greater in the autumn. M.C. Miller et al. (1976) observed up to 48% decrease in C-14 productivities during summer but slight stimulation in the winter. Lauer et al. (1974), again using net C-14 uptake as an index, measured a 40-67% decline in photosynthesis of phytoplankton as they passed through the Indian Point power plant on the Hudson River in the summer and spring, whereas no change was detectable in the winter.

Previous studies, however, did not always indicate beneficial effects in winter and detrimental effects in summer. At two estuarine power plants in Maryland, for instance, Mihursky (1971) measured a small (13%) reduction in net phytoplankton productivity in the summer, whereas Flemer (1974) found marked photosynthetic depressions (on the order of 95-98%) resulting from power plant operation in September. Gurtz and Weiss (1974) observed reduced C-14 production of heated samples in all seasons. A simulation model by P.C. Miller et al. (1976) indicated about 10% decrease in net productivity accompanying a 10°C temperature increase for mangroves. Morgan and Stross (1969) indicated a 15% decline in summer phytoplankton production at Chalk Point, Maryland (for temperatures 23°C) while winter photosynthesis was unaffected. However, photosynthetic rates for laboratory incubations at 8°C above control at winter temperatures were increased by half, possibly indicating mechanical or chlorine stress to entrained phytoplankton (in addition to temperature effects). Fox and Moyer (1973 and 1975) reported results which indicate a possible buffering effect of discharge canals. They found a small decrease in productivity across the Crystal River power plant condensers in April and June, but by the time the thermal effluent had traversed the length of the discharge canal, C-14 productivity was well above the level at the intake station. M.C. Miller et al. (1976) showed similar recovery trends in the discharge canal at the James Stewart generating station on the Ohio River. Hiroyama and Hirano (1970), Grayum (1973) and Tilly (1974) found virtually no effect of temperature on C-14 phytoplankton productivity. Tilly measured oxygen consumption of concentrated samples and found higher rates of plankton respiration in heated discharge waters.

Metabolism of benthic plants and whole communities affected by power plant effluents have been reported for a few cases. Cory (1974) found a slight increase in community productivity and a 70% increase in total respiration before and after initial operation of the Chalk Point plant, but factors other than the power plant (such as increased sewage input) may have contributed to this change. Jacobson (1976) found productivities in the Connecticut Yankee discharge canal almost two-thirds higher than in the adjacent estuary near the power plant intake, especially during winter months. The only other field measurements of ecosystem metabolism at a power plant were done at Crystal River, Florida, where Smith (1976) found a 50% reduction in total productivity in the shallow bay near the discharge plume, and McKellar (1975) observed consistantly higher turn-over rates and found a significant 15% decrease in total metabolism of the heated outer bay in the Fall. Young (1974a) found a slight stimulation of net productivity in the thermally affected salt marsh near the discharge, but decreased gross photosynthesis.

Thorhaug (1974) measured reductions of turtle grass net production ranging from 50-100% in an area (3×10^5 m^2) adjacent to the Turkey Point discharge. This community has apparently been partially replaced by another benthic plant assemblage, but its production has not been reported (Thorhaug, 1974). Vadas et al. (1976a) found macrophytic algal standing stocks reduced by about 76% since initial operation of the Maine Yankee power plant, but growth rates were not significantly affected. They (Vadas et al., 1976b) also observed both biomass and net production of Spartina alterniflora decreased by about 44% in the areas affected by power plant discharge. Using the seagrass growth and branch-density data of Ford et al. (1975), Kemp (1976) estimated benthic productivity for the estuary near the Anclote power plant in

Florida. Summer net production in the effluent area was depressed by 22% and winter production increased by about 35%.

Several microcosm studies of thermal effects on aquatic ecosystems have been published. Beyers (1962, 1963) observed that pond microcosms with production and respiration balanced and closed mineral cycles showed little effect of short-term 7°C temperature elevations. Phinney and McIntire (1965), however, found that community respiration of nutrient rich laboratory streams varied directly with temperature, and gross productivity also increased with temperature, as long as adequate light was available. With insufficient light no temperature effect was found, and it may be that the added thermal energy in heated ecosystems can be exploited only if light and nutrients are also readily available. Kelley (1971) studied microcosms adapted to different temperatures and also found a direct relationship between mean temperature and microcosm metabolism over the temperature ranges of his experiments. Copeland and Davis (1972) reported an anomalous pattern of increased community metabolism of heated pools in spring and summer, but decreased in winter. For the same microcosms Copeland et al. (1974) measured increased net algal production throughout the year, and Davis (1971) found a direct relationship between temperature and community respiration up to 30°C.

Zooplankton Entrainment

Numerous investigators have reported mortalities incurred to zooplankters as they pass through power plant condenser systems. The level of mortality was a function of type and standing stocks of zooplankton, temperature rise across the condensers, maximum temperature experienced, length of time held at elevated temperature, and other factors, including exposure to chlorine and mechanical shear. Mortality rates varied, but at a given site summer values were generally highest.

Davies and Jensen (1974) observed copepod mortality rates between 0 and 70%, while Gonzalez (1973) found two congeneric species of Acartia having mean summer mortality rates of 35 and 71%, with the more tolerant species being naturally dominant in the estuary during warmer months. Mean annual rates of zooplankton kill were 18.3 and 25.5% at two Lake Ontario plants (Storr, 1974). Very low mean rates of about 6% were reported by Lackey (1974) for the Turkey Point plant in Florida and by Icanberry and Adams (1974) for four coastal power plants in California. Heinle (1969) and Heinle et al. (1974) measured no significant copepod mortalities except during plant chlorination cycles. Carpenter et al. (1974 a, b), on the other hand, have measured annual mean rates of holoplankton kill at 70% and they attribute this primarily to a mechanical stress as inferred from tests with circulating water being pumped when the power plant was not operating. Similar inferences have been drawn by others (Industrial Bio-test, 1972; Benda et al., 1975). Carpenter and colleagues calculated that 0.5% of the zooplankton production in all of Long Island Sound is cropped by power plants, while Polgar et al. (1976) estimated 2% loss of zooplankton due to entrainment at power plants on the Potomac River. For the Crystal River plant Alden et al. (1976) reported about 10% copepod mortality during most of the year, but this rate increased to 80% at mid-summer, and this agrees well with the summer mortality rates described by Reeve (1970) and Reeve and Cosper (1970) at Turkey Point. Benda and

Gulvas (1976) observed direct relationship between mortality rate and ambient temperature, with mortality ranging from 6-15% when temperature $< 34^{\circ}C$ but ranging from 75-90% when temperature $\geq 34^{\circ}C$. Drew (1975), continuing the earlier work of Fox and Moyer (1973) at Crystal River power plant, showed that adenosine-triphosphate (ATP) changes between intake and discharge were an adequate index of long-term trends of zooplankton entrainment effects, although they did not correspond well with daily mortality rates as measured by Alden (1976).

Entrainment mortality inflicted on meroplankton (larvae of larger animals) appears to be generally higher than for copepods. Kennedy et al. (1974 a, b) found that bivalve larvae suffered 63-100% losses at laboratory temperature elevations of 10-12°C for about 1 hr, while Nelson (1973) indicated about 80% mortality for larvae of the Pacific oyster. *Neomysis* shrimp were killed at a rate of 30-50% at Indian Point in spring and summer (Lauer et al., 1974) and at rates up to 67% throughout the year at a plant in the San Joaquin Delta of California (Chadwick, 1974). Marcy (1971, 1974) measured extremely high levels of mortality (93-100%) for fish larvae and juveniles passing through the Connecticut Yankee cooling system from May to August, and 80% of this loss was due to mechanical stress. He calculated that this mortality represented about 4% of the total populations flowing past the plant intake. Menhaden and river herring juveniles were entrained at an estimated rate of 7-165 million per day at Brayton Point in the summer of 1971 with complete mortality, and most of these had been physically mascerated (EPA, 1972). Chadwick (1974) found striped bass larvae mortality rates at 5-58% in the laboratory for a temperature rise of 6°C and ambient spring or fall conditions.

Nekton Impingement on Intake Screens

Very little published information exists regarding the rates and types of fish which are killed by impingement on power plant intake screens. Most of the existing information is in the form of environmental impact statements and supporting research reports. Clark and Brownell (1973) summarized some of this unpublished literature and found impingement rates ranging from 350,000-6 million fish per year including a variety of species such as white perch, menhaden and river herring.

Table 2 summarizes impingement data available for coastal and estuarine plants in the U.S., and there appears to be a general trend for maximum impingement rates to occur during the winter, even though estuarine nekton populations probably tend to be greater in the summer. Landry and Strawn (1974) sampled the intake screens at the P.H. Robinson plant on Galveston Bay and found that impingement rates corresponded well with fish stocks measured in the intake canal by otter trawl. The nekton impinged were predominantly menhaden, croaker, anchovy and blue crab, and even though screened fish were sluiced into the discharge canal, mortality rates appeared to be high. Grimes (1971, 1975) made monthly observations of impingement at the Crystal River plant in 1969 and 1970, while Snedaker (1974b) continued to do weekly sampling for 1972 and 1973 at this same plant. In both studies mid-winter peaks in entrapment were observed, but Grimes' data, although consistent between years, indicated substantially fewer fish killed than did Snedaker's data. This difference is possibly attributable in part to the more comprehensive sampling techniques of Snedaker.

Table 2. Fish entrapment on intake screens at several coastal power plants in the United States.

Power Plant Name and Location	Cooling Water Flow (m^3/min)	Major Kinds of Fish	No. Killed per Year	Kilograms per Year	Comment
Millstone Unit 1[a] Niantic Bay, Conn.	1590	Finfish Crabs, Lobsters Menhaden	12,775 2,190 2,000,000	---	Aug-Oct
P.H. Robinson[b] Galveston Bay, Tex.	2950	Finfish Crabs	4,495,000 350,000	25,180	Peaks in Mar
Indian Point[c] Hudson R., N.Y.	4500	White perch etc., Striped bass	6,000,000 500,000	---	Peaks in Feb (predicted)
Brayton Point[c] Narragansett Bay, Mass.	2380	Menhaden Flounder Silver sides	350,000	---	Heavier in Nov-Mar
Haddam Neck[d] Conn. R., Conn.	1500	Perch Herring Catfish	779,000	3,682	---
Oyster Creek[e] Barnegat Bay, N.J.	1630	Winter Flounder Menhaden Blue Crabs Other fish	480,000 500,000 640,000 177,000	---	---
Surry Power Plant[c] James R., N.J.	6360	River herring	6,000,000	---	Oct-Dec, Part Power Runs

Table 2. (Continued)

Power Plant Name and Location	Cooling Water Flow (m^3/min)	Major Kinds of Fish	No. Killed per Year	Kilograms per Year	Comment
Crystal River[f,g] Gulf Coast, Fla.	2410	Batfish, Sea cat	155,000		1969, Mar peak
		Batfish, Anchovy	125,000		1970, Feb peak
		Batfish, Thread-fin herring	796,673	4,223	1973, May peak Feb peak
San Onofre[h] Pacific Ocean, Cal.	1325		---	13,640	Offshore Conduit intake
Palisades[i] Lake Michigan, Mich.	1840	---	489,000	14,900	Peak catches in late fall and early spring

[a] AEC (1973a); [b] Landry and Strawn (1974); [c] Clark and Brownell (1974); [d] AEC (1973a);

[e] AEC (1972d). Given is no. fish caught on screens; not all these were killed; [f] Grimes (1975);

[g] Snedaker (1974b); [h] AEC (1975); [i] Brenda and Gulvas (1976), not a coastal plant.

Clark (in Clark and Brownell, 1973) made experimental observations at the Indian Point Plant on the Hudson River under varied pumping conditions. Impingement rates increased markedly when intake water current exceeded velocities of about 18.3 m/min (1 fps). Based on life history information and certain assumptions about impingement susceptibility, Lawler et al. (1974) and C.A.S. Hall (1975) developed simulation models to predict the impact of power plant entrainment mortalities on the striped bass population in the Hudson River. The impacts of larval entrainment on adult populations predicted by these models range from virtually none in the former to a 50-60% decrease in Hall's model under conditions with all planned power plants in operation.

Review of Methods for Environmental Planning and Evaluation

Rational decisions between alternative sites for power plants and alternative thermal (and other) waste management schemes require: first, a method for predicting the effects of each option on the regional systems and on the adjacent ecosystems; and second, a technique for comparative evaluation of economic and ecological effects to facilitate selection of the best plans. Techniques which have been used in decision-making processes for environmental planning and impact assessment are reviewed under the following headings: evaluation techniques; predictive models; and methods that couple evaluation and modeling.

Evaluation with Economic Analysis

The method of comparative costs is used to choose between alternative economic designs for human systems, where the option having the lowest total monetary cost is considered preferrable. Burnham et al. (1968) employed the technique for power plant siting in the Pacific Northwest and considered environmental effects only in terms of cost to mitigate them. A multi-objective form of this technique was modified by Isard et al. (1972) to select between various recreation-complex options, where environmental costs in adjacent estuaries were compared in terms of economic cost of equivalent fishery loss.

A more complex version of cost analysis is the benefit-cost analysis (BCA), widely used by the Corps of Engineers, Soil Conservation Service, Bureau of Land Management and others for public water resource project evaluation. BCA attempts to achieve so-called optimum resource allocation where a given resource is distributed such that the economic output value of the particular use (marginal product) is greater than or equal to that of any other potential use. The objective of most BCA is to maximize economic efficiency and/or net economic output. Dollar benefits and costs projected for the future are put in terms of "present economic worth," based on the notion that, in an expanding economy, money in the present can earn money in the future. The relationship between benefits and costs can be expressed either as a ratio (Eq. 1) or a difference (Eq. 3):

$$\frac{B}{C} \text{ ratio} = \frac{\sum_{t=0}^{n} \frac{B_t}{(1+R)^t}}{\sum_{t=0}^{n} \frac{C_t}{(1+R)^t}} , \qquad (1)$$

$$N = \sum_{t=0}^{n} \frac{B_t - C_t}{(1+R)^t} , \qquad (2)$$

where

N = net benefits,

B_t = benefits at time, t,

C_t = costs at time, t,

t = time,

R = discount rate.

There is considerable controversy as to the proper discount rate to use in converting time series of benefits and costs to present worth. Larger discount rates favor economic events closer to the present, so that future dollars are worth less than present dollars. Most federal water resource projects are conceived with costs in the present and benefits in the future, and the low discount rates which are commonly used thus tend to increase the B/C ratio. Environmental costs (at present or in the future) are seldom considered with this method.

The details of the BCA method are summarized in Howe (1971), James and Lee (1971) and Prest and Turvey (1966). Maass (1966) suggested that multiple objectives other than short-term maximization of economic efficiency should be considered for this method. Haveman (1965) showed the extreme effects of slight changes in the discount rate assumption, and he calculated that over 50% of the federal project funds spent in the southern U.S. between 1946 and 1962 would, under one set of reasonable assumptions, have been spent on projects with B/C ratio < 1.0. A major criticism of this technique for environmental decisioning, however, is its inability to quantify environmental costs, which are by definition external to traditional economic models. Etzold (1973) contended that the willingness of consumers to pay for environmental amenities is a measure of environmental values in the BCA. However, Müller (1974) rejected this proposition on the grounds that prices and values do not reflect the interrelationships between environment and economy, and that consumers operate primarily with short-term interests in mind.

Evaluation with Subjective and Mixed Units

The National Environmental Policy Act (NEPA, 1969) established as a national objective the development of cost-benefit methodologies which consider ecological and economic values in environmental impact assessment. In response to this, the former Atomic Energy Commission (AEC, 1972a) developed a benefit-cost technique for use in environmental impact statements for nuclear power plants and other AEC regulated projects. This method calls for the tabulation of effects both to people and to nature for various project alternatives. Evaluations are done in terms of different units of measurement ranging from pounds/year, to acres, to rems/year, to hours/year, to dollars/year, to qualitatively descriptive words, thus making a decision between alternatives difficult because different kinds of effects are not directly comparable.

Several methods have been suggested using a subjective common parameter for comparison of environmental values with economic. Helliwell (1969) proposed a technique which categorizes wildlife resources into four classifications (production, potential production, education, and recreation) and assigns an arbitrary index for these which is based on such parameters as species diversity. The numerical index, then, is subjectively convertable to monetary units. Cairns (1976) indicated a similar subjective rating scheme to evaluate the vulnerability of ecosystems to power plant effects. He used the following criteria for this index: 1) susceptibility to irreversible damage; 2) elasticity; 3) inertia; 4) resiliency.

Leopold et al. (1971) proposed the use of a large evaluation matrix with natural system components as matrix rows and categories of impact as column headings. The matrix is used by assigning subjective numbers to each category at the intersections of rows and columns in the matrix to indicate the relative magnitude and importance of each impact on a system component. However, intersections of the Leopold matrix do not consider chains of interactions between environmental variables and feedback properties. Nonlinear responses such as synergistic or internally-damped behavior can not be taken into account. Only environmental effects are considered, and no format is offered for comparing various economic and environmental factors.

A modification to this basic matrix evaluation technique is the "Delphi process" proposed by Dee et al. (1973), which employs an interdisciplinary "panel of experts" to decide on the functional relationships and relative importance of matrix categories. The method allows consideration of interactions between parameters, but suffers from its subjective nature. Thus it would not be too surprising if one group of "experts" were to develop a system of functional relationships (for each position on the matrix) that was vastly different from that developed by another group of "experts" (depending on their interests, biases, and points-of-view). Cordara and Malloy (1973) used a similar method to evaluate potential coastal power plant sites on Long Island.

Evaluation with Maps of Spatial Parameters

Another qualitative technique which introduces spatial relationships for environmental, social and economic parameters between subsystems has been developed by McHarg (1969 a, b). Here, natural and urban lands are inventoried and categorized by present and potential land uses. Separate overlay maps are made with varied shading to indicate compatibility of given lands for development alternatives according to estimated effect of, and on, each of several factors such as soils, hydrology, topography, vegetation, economic activities, cultural uses, and public health. Thus, the most suitable areas for given land use are those with darkest (or lightest) shading from a composite of overlaid maps. Zieman (1971) used a modified version of this procedure to evaluate eight highway alignment alternatives in north Georgia, and they employed a random error-weighting scheme for these parameters, the effects on which are not precisely calculable, to indicate sensitivity of analysis. They found that their evaluations for each of the four best routes were not statistically different. Murray (1972) and Niemann and Miller (n.d.) have employed a computerized mapping technique for highway location planning based on the "McHarg concept" where spatial cells were defined with dimensions of 4 and 102 ha (10 and 250 ac) respectively. Subjective weighting scales for various parameters and various degrees of impact are programmed into computer mapping routines which use 10-12 grades of shading. These techniques allow the introduction of spatial factors in environmental planning; however, they require subjective weighting scales and do not consider interactions between land-use factors.

Evaluation with Operations Research Methods

The optimization techniques of operations research have found several applications in environmental planning, and Swartzman (1972) reviewed the concepts and utility of these methods for ecosystem management. The most versatile and commonly used method is the linear programming version. This is a static methodology which maximizes or minimizes an objective function, F (within a given set of physical constraints), linearly relating system variables at a given time. Solution techniques generally employ algorithms which search for that vertex on the boundary determined by constraint equations which maximizes the objective. This can be expressed mathematically in subscript notation,

$$\text{maximize (min) } F = \sum_{i=1}^{n} c_i \, x_i \tag{3}$$

where,

$$\sum_{i=1}^{n} a_{j,i} \, x_i \leq b_j \quad , \tag{4}$$

and

$$x_i \geq 1 \quad \text{for all } i \quad ,$$

and

$a_{j,i}$ = coefficients of constraint functions

b_j = limits of constraint

c_i = coefficients relating variables in objective function

x_i = system variables.

The major problems with this procedure are that it is limited to the use of linear relationships between variables, and that time is not an explicit independent variable. As commonly applied, objective functions are formulated in monetary terms and do not consider all environmental values (although this could be done). Rothschild and Balsiger (1971) have used this method to allocate salmon harvest among the days of the salmon run to maximize the value of catch while providing sufficient escape from harvest to maintain fishery stocks. Wardle (1965) used linear programming to maximize net, discounted revenue from harvest of mixed hardwood and conifer forests by optimizing planting and cutting schemes.

Non-linear and stochastic optimization programming methods are available; however, solution techniques for even simple non-linear systems are limited. Probabilistic systems often require solution via Monte Carlo techniques which are expensive and not necessarily reproducible. Dynamic programs enable optimization over a time course which may be subjected to model policy decisions at each stage in the process. A basic, though not necessarily realistic, assumption underlying all dynamic optimization programming is the Markovian property that, at each step of a process, the next optimum stage is a function only of the present stage and not of the previous history of steps. Dynamic programs are nearly impossible to solve for detailed, non-linear functions. Swartzman (1972) developed a very large linear optimization program to maximize deer harvest within a given state without overkilling the population. Swartzman (1972) also conceptualized (but did not solve) a non-linear optimization model utilizing the subjective environmental quality units of Dee et al. (1973) for watershed management.

Predictive Models: Input-Output

Wilson (1968) and Bishop et al. (1974) reviewed some of the models which have been used in urban and regional environmental planning. An accounting model procedure developed for economic analysis by Leontieff (1970) has found some application in environmental planning. This input-output method allows examination of general steady-state conditions of production, and has often been used to estimate the impact on all system sectors arising from a change in final economic demand in one or more sectors. In vector form this is expressed as:

$$\underset{\sim}{Q} = A\,\underset{\sim}{Q} + \underset{\sim}{F} \tag{5}$$

where

$\underset{\sim}{Q}$ = vector of output value for all sectors

$\underset{\sim}{F}$ = vector of final demand (i.e., inputs which are not strictly a function of output)

A = matrix of input value coefficients.

This expression is then solved for Q so that,

$$Q = (I - A)^{-1}\,F \tag{6}$$

where,

I = identity matrix.

Isard et a. (1972) developed an input-output matrix which couples ecological processes (as monetary value of fisheries) to economic sectors and evaluates recreation alternatives in terms of economic efficiency. Wilen (1973) constructed a similar, general input-output model linking an ecological submodel to an economic submodel with energy and material exchanges between the two. He suggested that using models such as this to estimate the impact of changes in the economic sector on ecological productivity (in energy units) and comparing this to the modified economic productivity (in money units). The main drawback of input-output models is that they must assume linear functions, and calculations can only be done for static conditions. Wilson (1968) also pointed out that the final demand sector involves complex processes which should, themselves, be modeled. The input-output technique does not explicitly consider external energies which drive the production processes in each sector and therefore is limited in addressing questions which pertain to these external factors.

Simulation Models for Prediction

Simulation models describe systems as sets of differential, difference, integral or summation equations. They simulate temporal dynamics, with time as an independent variable. They can be made to simulate spatial characteristics, either aggregating state variables into clustered subunits of dependent variables, or as independent spatial variables, portrayed with partial differential equations. The use of simulation models for describing ecosystem dynamics has become relatively widespread (e.g., Patten, 1971; 1972 a, b; 1975a), but a recent comprehensive review by Wiegert (1975) indicates that only a limited number of these are finding specific application to environmental planning. A few highlights of those ecological models used in decision making are mentioned here.

Chen and Orlob (1975) developed aquatic ecosystem models to predict effects of alternative sites for sewage treatment facilities in the San

Francisco Bay — San Joaquin Delta region, and to study management alternatives for Lake Washington. Kelley (1976) reported on a model which predicts the effects of waste discharges on the Delaware River estuarine ecosystem. O'Connor et al. (1975) described several applications of their plankton model which relates waste discharges to eutrophication processes, and Park et al. (1975) have developed a complex model to study resource management problems in Lake George, N.Y. The EPA has been long involved in water quality modeling for basin planning impact assessment, and a guidelines publication (EPA, 1971) listed several of the commonly employed "prepackaged" models. At present, a large portion of the models for ecosystem understanding and management are being developed under the auspices of the International Biological Program (IBP), and most of these are included in Wiegert's review and are reported in the proceedings of a symposium series edited by Patten (1971a, 1972a,1975). Proceedings from two other symposia directed more at modeling for management problems are also available (Russell, 1976; Middlebrooks et al., 1974).

Mar and Newell (1973) have provided an assessment of selected enivronmental modeling efforts supported by the National Science Foundation. They said that many models had been developed with insufficient scientific basis and large-scale models tended to lack conceptual generality. Often large system models had been modified in favor of reduced process- or component-models, and even management models were developed without proper cognizance of model users. Mitchell et al. (1976) reported their evaluation of three IBP modeling programs, and indicated a serious shortfall in terms of model accuracy. They also concluded that several modeling groups had opted for models of components rather than large scale systems. Very few of the ecosystem models developed for management problems are well validated, particularly the large scale models (Mitchell et al., 1976). They are, nonetheless, tools of promising potential for predicting effects of alternative management schemes.

A few regional-level models have been recently developed. Watt and Wilson (1973) used a model with 14 subroutines to investigate various submodel processes involved in California planning policy decisions, but initial plans to build an integrated regional model were modified in favor of operative submodels (Mar and Newell, 1973). Craven et al. (1973) developed a simulation model comprised of four submodels: socio-economic; socio-political; ecological; and land-use. They tested the effects of various land development patterns in the Knoxville, Tennessee area. Antonini et al. (1974) coupled models of land-use and water budget to predict the effects of different development policies on reservoir sedimentation in a region of the Dominican Republic. This model, though somewhat limited in scope, demonstrated the marked difference in sedimentation rates resulting from various watershed practices. Koenig (1973) reports on five specific short-range resource management studies using decomposed models with the intention of reconstructing the system of study piecemeal. These studies range from sewage recycling to power plant siting.

Environmental Analysis with Coupled Modeling and Evaluation Methods

As described above, Isard et al. (1972) combined: a "gravity model" (in which the product of two populations is divided by a power function of the distance between population centers) to estimate demand;

an economic and ecological input-output model to test the economic effects of project options; and comparative costs methods to assess althernative marine recreation-complex designs in Duxbury Bay, Massachusetts. Russell and Spofford (1972) reported on an input-output model cast in a linear optimization program to maximize economic efficiency. The residuals of the input-output matrix were put into an environmental model to simulate waste dispersion and ecological damage, and the optimization model traded-off between environmental losses (as effluent charges) and industrial production output. The concepts of this analysis scheme were extended to a study of the Delaware River estuary (Spofford, 1973), where a complex linear optimization program linked economic costs to waste discharges predicted from an ecosystem model (Kelley and Spofford, 1977).

Bishop et al. (1974) reviewed the work of Myers (1973) on the Arizona Trade-Off Simulation Model which has been used by the state planning office to investigate policies on growth, environmental impact and land use. The model allows subjective trade-off between economic values (measured as employment) and environmental values (measured in the environmental quality units of Dee et al., 1970). Pavelis (1961) and Castle (1961) have suggested combining linear programming and simulation models with benefit-cost analysis for water resource planning. They argued that prediction of future conditions under alternative projects has been the weakest part of the benefit-cost analysis. Hydrologic simulation models such as that of Beard (1968) are available for predictive use in benefit-cost analysis but these do not consider ecological values.

Another regional simulation model for the Vancouver area was created by Goldberg et al. (1971) consisting of several submodels to simulate the effects of various public policy decisions. The submodels can be used to generate various indices as discussed by Holling and Goldberg (1971), and policy decisions are built into the model when indices exceed thresholds. Robinson (1973) attempted to combine standard air and water quality models with input-output analysis to investigate the effects of waste abatement on the regional economy of the lower Connecticut River basin.

Cooper (1969) suggested coupling of optimization and simulation models. Swartzman and Van Tyne (1972) used a combination of a nonlinear simulation model (employing stochastic forcing functions) with a linear optimization program to develop annual management schemes for Australian arid grassland-shrub range. The two programs were coupled by optimizing "management coefficients" in the simulation model year-by-year. The system was designed to maximize long-term profit over 10 yrs with policy adjustments at annual intervals, and the year-by-year management program produced 12% more profit than constant management. The utility of this coupled model was further developed by Jameson (1973). Considering the power plant question, Buchan (1972) developed a statistical model of an aquatic ecosystem to simulate effects of alternative waste heat discharge methods on species diversity, and proposed that information from models be channeled directly into the political-legal decision processes.

Recently, at the University of Florida several studies combining regional and/or ecological simulation models with energy calculations and cost-benefit analysis have been applied to environmental planning problems. Mitsch (1975) modeled the effects of sewage recycling in cypress domes and lake ecosystems in Florida and used energy cost-benefit to show that this sewage treatment was more economic and energetically adaptive than conventional tertiary treatment. Boynton (1975) used an ecosystem model and a regional model to test the effects of several planning policies on an oyster fishery and a county economy. He also applied energy calculations to evaluate plans for an island development and a dam project. In a large comprehensive study Odum and Brown (1975) used these techniques to evaluate alternative land, fuel and water use policies in South Florida in terms of a competitive balance between the energies of nature and those of man.

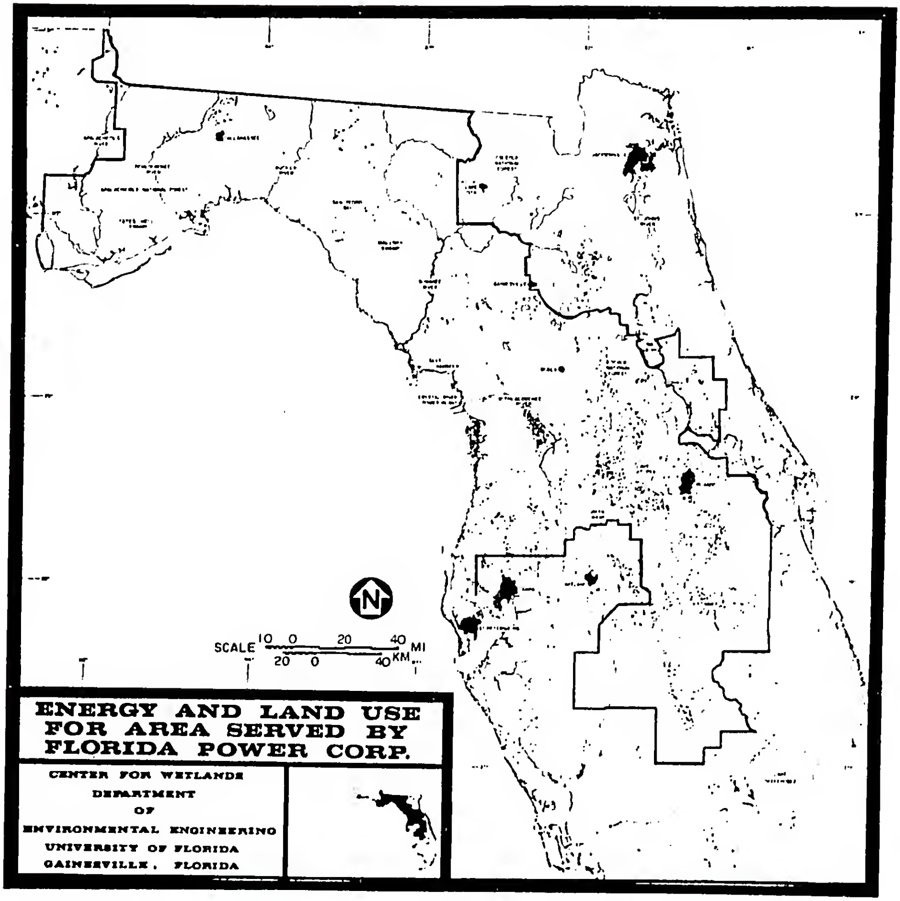
Description of the Study Area

The theoretical questions raised in this study were considered for the specific case of the Crystal River power plant on the northern Gulf Coast of peninsular Florida.

The Powershed

The Crystal River plant is a major generating facility for the Florida Power Corporation (FPC). The two units presently operating at Crystal River comprise about 21% of the company's generating capacity, and the third unit will increase this to 35%. The Crystal River station is connected into the company's electric power grid which serves a 32-county region in the northwestern part of Florida as shown in Fig. 3. At its present capacity FPC produces about 26% of the state's electric demand and the addition of Unit 3 will raise this to about 32%. Once it enters into the grid system, electricity from

Figure 3. Map showing some geographic features of region served by Florida Power Corporation.



ENERGY AND LAND USE FOR AREA SERVED BY FLORIDA POWER CORP.

CENTER FOR WETLANDS
DEPARTMENT
OF
ENVIRONMENTAL ENGINEERING
UNIVERSITY OF FLORIDA
GAINESVILLE, FLORIDA

Crystal River is indistinguishable from that generated at any other plant, and it may be consumed at any point in this "powershed." Direct economic and environmental effects of electricity generated at this power plant are felt throughout the powershed.

The FPC powershed covers 25 whole counties and varying portions of seven others. It is relatively rural part of Florida, including some 30% of the state's area but only 27% of its people (BEBR, 1975). Agriculture is important with about $450 million worth of crops sold in 1969, representing 40% of the state gross crop sales (BEBR, 1975). Most of the agricultural production in the powershed is from mixed crop truck-farms. Pine flatwoods were the dominant natural vegetation in the region and much of this land has been converted to pine plantation. The region includes the Suwannee River and the lower part of the Apalachicola River, and numerous lakes, including Lake Apopka and Orange Lake, are scattered throughout the area. There are various moderate-sized cities in the powershed, and the largest of these are Tallahassee, St. Petersburg and Orlando. Disneyworld is the central tourist attraction in the region which hosted an estimated 39% of the state's visitors in 1972 (Div. Tourism, 1972).

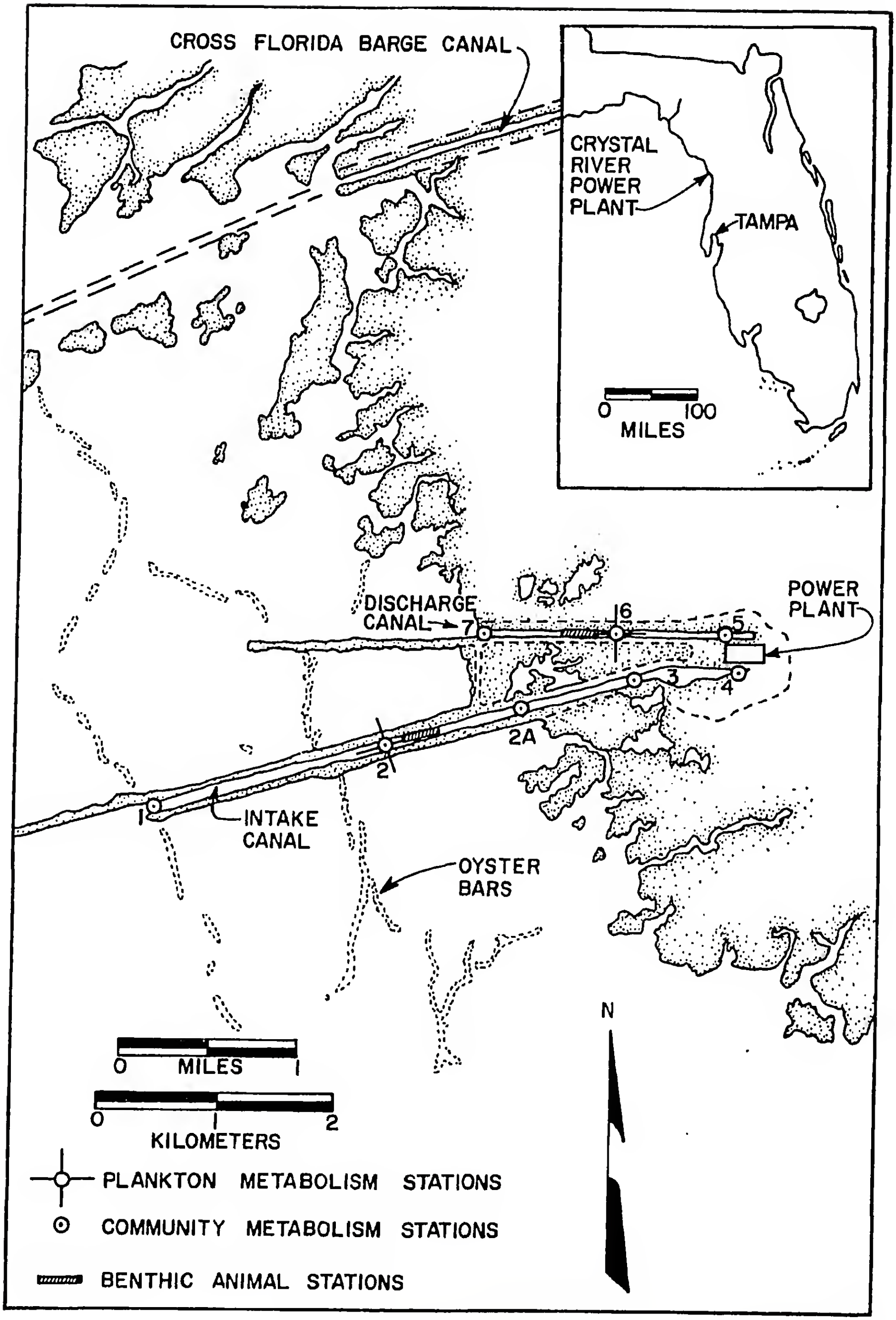
The region of study occupies about 496 km (308 mi) of the state's total 2160 km (1350 mi) of smoothed length of coastline (BEBR, 1975), and this coastal edge extends from Tampa to Apalachicola (see Fig. 3) and includes the largest stretch of relatively undeveloped coast in Florida. Commercial fishing is important in this area, but most of the catch is dominated by lower market value species such as blue crabs and mullet. However, valuable shrimping enterprise is important in the region, and the Apalachicola Bay oyster industry is the second largest in the country. The total marine area for the Crystal River power plant region is designated as the Gulf Coast strip within the powershed boundaries extending gulfward to where freshwater runoff is mixed to 95% seawater. This defines a coastal area 17 km (10 mi) wide and 496 km (308 mi) long.

The Power Plant and Estuary

The plant site shown in Fig. 4 is in Citrus County about 12 km north of the town of Crystal River. During this study two oil-fired generating units were in operation with a combined capacity of 897 megawatt (Mw) and a once-through cooling water flow of 2410 m^3/min. The maximum temperature rise across the condensers was designed at 6.1°C (11°F). Unit 1 began operation in July 1966, and Unit 2 in November 1969. A third 855 Mw nuclear-powered unit is scheduled for operation by the end of 1977. This unit will require an additional 2580 m^3/min of cooling water and the combined system will have a net temperature-rise of about 8.1°C (14.5°F).

The coastal shelf adjacent to the plant site has a shallow sloping bottom (45 km to the 9 m contour) and extends relatively far (230 km to the 100 m contour) into the Gulf of Mexico (Jones et al., 1973). This area is part of what Tanner (1960) and Walton (1973) have classified as the low wave-energy section of the Florida Gulf Coast. The topography of this area is characterized by limestone karst, typical of this portion of west-central Florida. The immediate coastal area contiguous to the plant site is comprised of a series of shallow basins separated by oyster reefs. Two major freshwater sources to the area are the Crystal River 4.8 km to the south and the Withlacoochee River 6.4 km to

Figure 4. Estuary adjacent to Crystal River power plant showing intake and discharge canals, and locations of field sampling stations.


CROSS FLORIDA BARGE CANAL
CRYSTAL RIVER POWER PLANT
TAMPA
0 100
MILES
DISCHARGE CANAL
7
6
5
POWER PLANT
3
4
2A
2
1
INTAKE CANAL
OYSTER BARS
0 MILES 1
0 1 2
KILOMETERS
N
PLANKTON METABOLISM STATIONS
COMMUNITY METABOLISM STATIONS
BENTHIC ANIMAL STATIONS

the north. The mean combined flow of these rivers was 3340 m^3/min in 1974, which is about 1.4 times the present power plant circulating water flow. The Withlacoochee River flows into the Gulf end of the unfinished Cross-Florida Barge Canal (15.3 km long) at its eastern-most extremity. Spoil islands from the Barge Canal continue about 6.5 km into the Gulf, and these, as well as the cooling water canal dikes for the power plant, influence local hydrographic circulation patterns.

The estuary adjacent to the power plant is characterized by five ecological subsystems: 1) an inner bay; 2) an outer bay; 3) the salt marsh; 4) the oyster reefs; and 5) the power plant intake and discharge canals. After passing through the 4 km long discharge canal, the heated plume flows over the shallow inner bay, which is about 1 m deep and contains mixed benthic communities of sea grass, algae, oyster and mud associations. Rising tides push the warmed water over the adjacent tidal salt marsh, which is dominated by black rush, Juncus roemerianus. Seaward of the inner bay are deeper outer basins (about 2 m mean depth) in which plankton and oyster reef ecosystems become more important. Oyster reefs, which comprise about 5% of the bay area are scattered throughout the immediate offshore area.

The Cooling Water Canals

The intake and discharge canals have been cut through the salt marsh and coastal bay systems west of the plant site, displacing approximately 1.1 km^2 of marsh and 1.9 km^2 of bay (Fig. 4). The intake channel extends from the plant about 12.5 km into the Gulf of Mexico, and is laterally confined with double-bulk-heading for the first 5 km.

The mean depth of the intake canal is about 6.5 m compared to the 1-2 m depth of the surrounding bays, and the width at mean low water (MLW) varies from 90-110 m. The double-bulkhead portion of the discharge canal extends approximately 2 km due west from the plant, and the total length of the dredged channel is about 3.8 km. The discharge canal was designed with a smaller cross-sectional area (4.5 m deep, 60 m wide) so as to maintain a relatively high velocity, 20 cm/sec, and assure adequate lateral flow entrainment and mixing upon discharge to the shallow bay receiving waters. The intake canal is wider and deeper than the discharge to accomodate the movement of fuel barges to and from the plant, and its water velocity averages about 9 cm/sec.

The bottom material of both canal channels varies but is primarily comprised of a clay-silt-sand matrix similar to the sediments of the adjacent bays with organic content ranging from 3-6% dry weight (Cottrell, 1974). The intake canal has wide, shoaled intertidal areas, and its banks slope gradually until about 1-2 m mean depth, at which point they become steeper (about 1:3) and continue to the channel bottom. The substrate on the sides of both canals is dominated by limestone talus material ranging from 0.1-0.5 m diameter, which completely buries the shelf in many areas. The sides of the discharge canal are not shoaled and have uniform slope of about 1:1 to the base of the channel (Carder et al., 1974b).

Approximately 47% of the water entering the canals is taken directly from the deeper offshore systems, while 27% originates from the area immediately south of the canal intake and the remaining 26% is drawn from the nearshore shallow bay systems south of the canal spoil bank. The warm, brackish nearshore water enters the canal in the latter stages of an ebb tide, and this water procedes plantward in the canal during low water, flood and high water tidal stages. During the flood tide cooler, saline waters of Gulf origin enter the canal, forming a pocket of less-dense water which moves down the canal and gradually mixes with the underlying waters before being drawn into the plant (Carder et al., 1974a). The canal waters, which have a combined residence time of about 24 hrs in the canal-power plant system, therefore have characteristics of both nearshore and offshore ecosystems. The intake canal water is generally clearer than the swifter discharge canal water, but both canals regularly experience turbid waters resulting from barge movement in the intake canal.

Previous Research at Crystal River

Prior to initial power plant construction at Crystal River very few ecological investigations of this estuarine area had been reported. Ingle and Dawson (1952), however, estimated oyster growth rates on reefs near the present power plant site. Dawson (1955) later studied the distribution of oysters at Crystal River in relationship to hydrography. Phillips (1960) described the relative composition of benthic macrophytes. During the early phase of power plant operation (Units 1 and 2), the Florida Department of Natural Resources conducted environmental studies in the estuary. Lyons et al. (1971) found benthic invertebrates to be distributed near the power plant more in relation to salinity than temperature gradients. Steidinger and Van Breedveld (1971) studied the relative abundance and diversity of benthic algae in the Crystal River area. They determined that control stations had considerably greater species diversity than discharge stations, but that the composition of the predominant algal community was about the same in both areas. In a symposium on the effects of elevated temperature on oysters from Crystal River,Quick (1971) reported that prolonged laboratory exposures of oysters to 35°C resulted in decreases of glycogen content and reduced gametogenesis (Burklew, 1971). However, field measurements of temperatures of oyster tissue indicated that under natural conditions temperatures approaching 50°C were experienced by oysters at low tide (Ingle et al., 1971). Nekton and other components of the Crystal River estuarine ecosystems were studied by Grimes (1971), Grimes and Mountain (1971), and Mountain (1972). They indicated that growth and abundance of selected nekton species were not significantly different between control and affected areas. In the shallow bays species diversity of fish was higher in discharge areas during winter but higher in the control areas during summer. As previously mentioned Grimes (1971, 1975) also monitored fish impingement on the power plant intake screens. Heavy metal concentrations were measured in oyster tissues from intake and discharge canals, and there were significantly higher concentrations of Zn and Cu in the discharge oysters.

With the planning of a third, nuclear unit at Crystal River, an extensive ecological research program was initiated, and the present study was a part of this effort. Standing stocks, distribution and diversity of benthic macrophytes (Van Tine, 1974), benthic invertebrates (Evink and Green, 1974), and nekton (Adams, 1974) were measured during 1973 and 1974. Migration of blue crabs was studied (Adams et al., 1974; Oesterling, 1973, 1976), and the impingement of crabs and other nekton, both juvenile and adult, on the power plant screens was measured

(Snedaker, 1974 a, b). Food habits of adult and juvenile fish in the bays were quantitatively investigated by Bolch et al. (1971), Adams (1972) and Carr and Adams (1973). Sediment composition, distribution and movement were examined by Griffin (1971) and Cottrell (1974), and the estuarine hydrography was described in detail by Carder et al. (1973, 1974 a, b), including the development of a computer model of the thermal plume. Data on nutrients, organic matter, chlorophyll-a and carbon-14 productivity have been provided by Gibson (1975) and McKellar (1975). Zooplankton biomass, numbers and diversity were reported by Maturo et al. (1974) in some detail, and zooplankton entrainment mortalities were measured by Alden (1976) and Drew (1975), while zooplankton respiration was reported by McKellar (1975). Total community metabolism was studied and ecological models were developed for the bays (Smith et al., 1974b; McKellar, 1975; Smith 1976) and the salt marshes (Young, 1974 a, b) near Crystal River. Lehman (1974) investigated standing stocks, diversity and metabolism of oyster reef ecosystems and used a simulation model to investigate relations between oyster biomass, species diversity and oyster spat. Biomass, diversity and trophic habits of fish inhabiting the tidal salt marsh creeks were thoroughly studied by Homer (1974, 1976).

METHODS

Three categories of methods were employed in this study: (1) simulation models; (2) ecological field measurements; (3) and calculations of energy cost.

Modeling Methods

Models were developed in this study to help determine: (1) what field measurements were most important; (2) proper data organization for overviews of systems; (3) energy relationships between system components; (4) the consistency of theoretical concepts with empirical facts as indicated through simulation; and (5) how estuarine systems might respond to changes in power plant operation. Models were conceptualized for systems at three scales, including the region, the estuary and the power plant canals. Computer simulations were done for the estuarine model.

Conceptualizing and Evaluating Models

Important storage components of the system being modelled were identified and incorporated into the model. Diagrammatic models were conceptualized using the energy circuit language symbols of H.T. Odum (1971, 1972c). As suggested by Odum (1972b) and Wiegert (1975), initial diagrams in this study included as much detailed understanding of the system as possible, but in subsequent drawings, related components and pathways were grouped and aggregated. Models were thus condensed by lumping some system parameters. The influence of those factors not explicitly included in the model were taken into account implicitly in calculations of pathway coefficients. In some portions of the model, where no direct measurements were available, values for pathway flows and state variable storages were deduced by difference, assuming that the rate-of-change of the variable was equal to zero. For this reason model quantification and calculation of pathway coefficients were done for mid-summer and mid-winter conditions when most biological phenomena are at peak and trough, respectively. During these maximum and minimum periods, the rate-of-change for system parameters would be closest to zero.

Examining diagrammatic portrayals of models, with measured numerical values (representing the actual system) placed on the diagram's pathways and storages, helped to give insight into the relative importance of various model parameters. Any flow into or out of a given storage which was less than 0.1% of others was generally ignored from further consideration. The average time constant or turnover time for each state variable was calculated as the mean storage value divided by the sum of the mean outflow rates. Any state variable whose turnover time was four or more orders-of-magnitude less than those of the other variables, was either omitted from the model or treated as an algebraic constraint, rather than as a state variable (i.e., described with algebraic rather than differential equations).

Simulation and Validation

An aggregated model of an estuarine ecosystem interacting with the power plant at Crystal River was simulated on the University of Florida's IBM 370/165 digital computer using DYNAMO programming language. The behavior of alternative configurations for the primary producer component of this model was investigated initially on a system of two slaved Electronic Associates, Inc. Miniac analog computers. Here, model response was observed on a Miniac Oscilloscope Repetitive-Operation Display Unit (Mod. 34035) and recorded with a Bausch and Lomb, Houston Instruments plotter (Mod. 2000).

Models were run initially with coefficients calculated and validated for conditions representing an estuarine study area which was unaffected by the power plant (control area). The validity of the model was determined by subsequent simulations with pathway coefficients identical to those calculated for control conditions but forcing functions modified to represent conditions in the discharge estuary. A match of field data under both control and discharge conditions using the same pathway coefficients was considered to be satisfactory validation. Once the model had been validated, simulation runs were done with coefficients modified to reflect changes in external forcing functions which represented changes in cooling water systems of the power plant. Other simulations were done with changes in internal coefficients to determine the sensitivity of model behavior to various parameters.

Ecological Field Measurements

Measurements of the estuary's ecological characteristics which were made by other researchers, were assembled in this study according to planning models (see number 2 under "Modeling Methods"). Other field measurements were done as a part of this study to help characterize the structure and function of power plant canal ecosystems.

Total Community Metabolism

The metabolic activity of entire ecological communities in the cooling water canals was determined using diurnal oxygen changes in the free water with a modified version of the method developed by Odum (1956) after Sargent and Austin (1949). The analysis of diurnal oxygen curves is described by Odum and Hoskins (1958) and Odum and Wilson (1962) and use of the two-station adaptation of this method for flowing waters is demonstrated by Odum and Odum (1955) and Odum (1957). A total of 43 diurnal metabolism studies were performed on 17 sampling dates. More than half (9 of 17) of the metabolism experiments were done during the summer. Between June and September, measurements were spaced at about weekly or biweekly intervals, whereas fall, winter and early spring measurements were done in 4-5 day clusters. Separate analyses of surface and bottom water oxygen trends were made for the intake canal ecosystem during periods of stratification.

During each diurnal oxygen study duplicate samples were taken (approximately 5 min apart) at the surface and at about 1 m above the bottom (5 m deep) in the intake canal, and at the surface only in the discharge canal. Stations were sampled at about 3 hr intervals throughout a 24 hr period. During the first few studies 3-4 replicate samples were taken at each location and time; however, the small variance ($\sigma = \pm 3\%$) among replicates indicated that duplicate samples were sufficient for this system. Concurrent with each oxygen sampling temperature and salinity (T-S) profiles were measured for intake canal stations at 1 or 2 m intervals using a Beckman Model RD5-3 salinometer. Vertical T-S profiles (observed on July 10, and 11 and August 26, 1974) indicated that water in the discharge canal was vertically homogeneous, and therefore only surface temperature and salinity were routinely measured. The bottom water of the intake canal was sampled with a Wildco (Mod. 1120TT) 2.5 l, modified Van Dorn bottle. Dissolved oxygen (DO) samples were taken at 1 m intervals throughout the water column on several occasions (June 27, July 10 and August 26, 1974), and these indicated that the mean DO of surface and 5 m depth measurements was very close (± 2%) to the mean DO for the six 1 m interval samples. Dissolved oxygen was determined by the Azide modification of the Winkler technique (APHA, 1971) adapted for use with smaller collection bottles as described by Smith et al. (1974b) and Smith (1976).

The rate of change of DO in aquatic systems is a function of the two general physical processes -- advection and diffusion -- and the two biological processes -- production and respiration (Odum, 1956). Algebraically this can be expressed as,

$$\dot{Q} = P - R + D_{in} + A_{in} \qquad (7)$$

where $\dot{Q}$ = the rate of change of oxygen in the water; P = gross primary productivity; R = community respiration rate; D_{in} = net rate of diffusion into water (positive in, negative out); and A_{in} = net rate of advection into study area. Diffusion of oxygen across the air-water boundary was measured directly, and advection was accounted for by measuring oxgyen trends in sequential stations in uni-directional flowing waters (such as cooling water canals). Thus, after algebraically subtracting the effects of these physical factors, the remaining oxygen rate of change as described in equation (7) is the manifestation of P and R only.

For flowing waters the rate of oxygen change in an ecosystem between two sequential stations is calculated as the difference between upstream oxygen concentration at time t and the downstream concentration at time $t + \tau$, divided by τ, where τ is the time it takes for a parcel of water to flow from upstream station to downstream station. In the power plant canals at Crystal River, the ebb and flood of tides affect several parameters which are involved in the diurnal oxgyen metabolism calculation. These include flow time between stations, diffusion rate and water depth.

The time of flow between stations was estimated assuming that tidal flows were constant during the ebb, flood and slack periods of a given tidal cycle, but that cross-sectional areas changed at hour intervals. In this way mean velocities were calculated for the mid-point of an hourly interval, and distance traveled during each interval was estimated until the total distance between stations was exceeded by the sum of distances traveled in each hour. The flow time (in hours) was then equal to the number of hours needed to just exceed the distance between stations (t_L) minus the quotient of the excess (beyond downstream station) distance traveled (ℓ) to the average velocity in the last hour. An expression for estimating the flow time τ, in the canals as a function of tide is then

$$\tau = t_L - \left\{ \frac{\left[\sum_{t=0}^{t_L}\left[\frac{(F_{tide})_t + F_{plant}}{(A_x)_t}\right]\cdot(1\ \text{hr})\right] - L}{\left[\frac{(F_{tide})_{t_L} + F_{plant}}{(A_x)_{t_L}}\right]} \right\} \qquad (8)$$

where,

t_L = number of hours until distance traveled just exceeds L (hr)

ℓ = distance traveled between $t = 0$ and $t = t_L$ (m)

$$= \sum_{t=0}^{t_L}\left[\frac{(F_{tide})_t + F_{plant}}{(A_x)_t}\right]\cdot(1\ \text{hr})$$

F_{plant} = power plant pumping rate = 2410 m^3/min

F_{tide} = tidal flow (m^3/min) = $\pm\,(h)(A_s)/T$ (m^3/min)
(sign depends on direction of tide)

T = tidal period, excluding slack (min)

h = tidal range (m)

A_s = area of water surface from midpoint between stations to innermost end of canal (m^2)

L = distance between stations (m)

A_x = mean cross-sectional area of canal between stations (m^2)

$= A_{xm} + (Z_t - \overline{Z})\ W$

A_{xm} = cross-section area at mean low water (m^2)

Z_t = depth at time t (m)

Z_o = depth at mean low water (m)

W = mean width of canal between stations (m)

Locations for metabolism stations were selected so that flow times would be long enough for significant oxygen changes to occur between stations, but short enough so as not to involve too large a fraction of the diel period. Generally, flow times in this study ranged from 1-4 hrs, which is consistent with those used by Odum (1957), Edwards and Owens (1962) and Owens (1966). Some of the physical parameters involved in computation of τ are given in Fig. 5 and a representative tabular calculation of flow times between two canal stations at 1 hr intervals is given in Table 3.

The community metabolism for a given day can be calculated as the integrated change in oxygen concentration for a water mass flowing between stations, per time of travel between stations, times the mean depth during that time, minus the diffusion rate, and this is given in the following equations:

$$P_{net} = \int_{t_r}^{t_s} \left(\frac{\Delta C_t}{\tau_t} Z_t - D\right) dt \qquad (9)$$

$$R_{nite} = \int_{t_s}^{t_r} \left(\frac{\Delta C_t}{\tau_t} Z_t - D\right) dt \qquad (10)$$

$$D = k \left(\frac{S - \overline{C}_t}{S} \right) \qquad (11)$$

where,

P_{net} = net daytime productivity (g O_2/m^2-day)

R_{nite} = night respiration (g O_2/m^2-day)

ΔC_t = difference in oxygen concentration (g O_2/m^3) of upstream station at time $(t - \frac{\tau}{2})$ and of downstream station at time $(t + \frac{\tau}{2})$

k = diffusion rate coefficient which varies with tide (t O_2/m^2-hr)

Figure 5. Diagram of discharge canal illustrating the physical parameters involved in calculating flow time, τ, between stations 5 and 6.

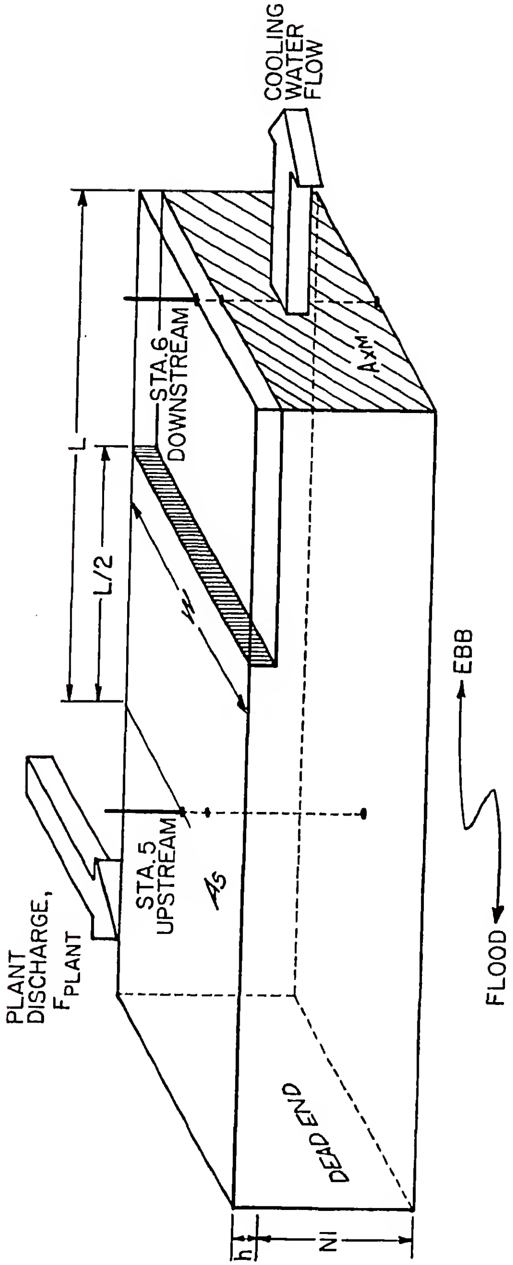

COOLING WATER FLOW
L
L/2
STA.6 DOWNSTREAM
W
A_{XM}
PLANT DISCHARGE, F_{PLANT}
STA.5 UPSTREAM
A_S
DEAD END
EBB
FLOOD
h
$\bar{Z}$

Table 3. Example of computation for flow time, τ, between discharge canal stations 5 and 6 on 1-2 July, 1974.*

Time of Day	Tidal Range, ft (cycle)	Tidal Vol., ft^3	Tidal Flow, cfs	Total Flow, cfs	Mean x-section, ft^2	Velocity, fps	Flow Time, hr
0400	1.0				2240	0.673	1.2
0500	(ebb)	0.63×10^6	+88	1508	2185	0.690	1.2
0600					2130	0.667	1.2
0700	(slack)	none	none	1420	2130	0.667	1.3
0800	2.6				2250	0.564	1.5
0900	(flood)	1.63×10^6	-151	1269	2360	0.538	1.5
1000					2470	0.514	1.6
1100	(slack)	none	none	1420	2580	0.550	1.5
1200				1420	2580	0.550	
FOOTNOTE	a	b	c	d	e	f	g

*Parameters involved in table computation: width of canal, W = 175 ft; distance between stations, L = 2950 ft; cross-sectional area, $A_{xm} = 1935\ ft^2$; surface area of tide, $A_s = 0.63 \times 10^6\ ft^2$ (Carder et al. (1974b).

Footnotes are explained for example calculation at time 0800:

[a] Tidal range is distance between low and high tide water levels, for given tidal cycle = 2.6 ft

[b] Volume of prism = (tidal range) x (surface area, A_s) = $(2.6\ ft)(0.63 \times 10^6\ ft^2) = 1.63 \times 10^6\ ft^3$

Table 3. (Continued)

[c] Tidal flow, $F_{tide} = A_s \times h/T = (0.63 \times 10^6 \text{ ft}^2)(2.6 \text{ ft})/3 \text{ hr})(3600 \text{ sec/hr})$
$= -151$ cfs (sign is negative since flood tide flows opposite discharge)

[d] Total flow, F_{total} = plant flow + tidal flow = 1420 + (-151) = 1269 cfs

[e] From tide charts water level at 0800 was 1.8 ft and the mean cross-sectional area $A_x = 1.8(w) + A_{xm}$
$= 1.8(175) + 1935 = 2250 \text{ ft}^2$

[f] The mean velocity during this hour is, then, $v = F_{total}/A_x = 1269 \text{ cfs}/2250 = 0.564$ fps

[g] At this speed 0.564 fps (3600 sec/hr) = 2030 ft will be traverse in 1 hr. This leaves (L - 2030) = 920 ft to sta. 6. Since the midpoint velocity at 0900 is estimated (by similar computation) to be 1937 ft/hr, the flow time, τ, starting at sta. 5 at 0800 = 1 + 920/1937 = 1.5 hours

S = oxygen saturation concentration for given temperature and salinity (g/m^3)

$\overline{C}_t$ = mean concentration of dissolved oxygen (g/m^3)

t = time (hr); as a subscript it indicates time-dependence

t_r = time of sunrise; t_s = time of sunset

Z, τ = as previously defined

Typical diurnal variations in oxygen, water depth, temperature, and salinity as measured for a metabolism analysis of the discharge canal are given in Fig. 6. The rate-of-change curve is deduced with the aid of hour-by-hour calculations as shown in sample calculation of Table 4 for the same data set. A continuous DO curve was assumed by plotting the average value from measurements at the start and the finish of the sampling. This, in effect, integrates the metabolism of the previous day with that of the current day. Percent saturation was estimated from the mean of temperature and salinity measurements made during the sampling using the equation and tables of Green and Carritt (1967), and this was used to calculate a diffusion correction for the rate-or-change curve.

The water column of the deeper intake canal was often stratified into two distinct layers as inferred from temperature, salinity and oxygen profiles. Therefore, water samples for oxygen analysis were drawn from both epilimnic and hypolimnic strata, and separate metabolism calculations were done for each. The main assumption involved in separating diurnal oxygen analyses into upper and lower subsystems is that the two layers move along the canal at about the same rate. Current meter surveys in the intake canal for a full tidal cycle (Carder et al., 1974) have indicated that this may be a

Figure 6. Typical diurnal variations in measured parameters for stations 5 and 6 on 1-2 July 1974.

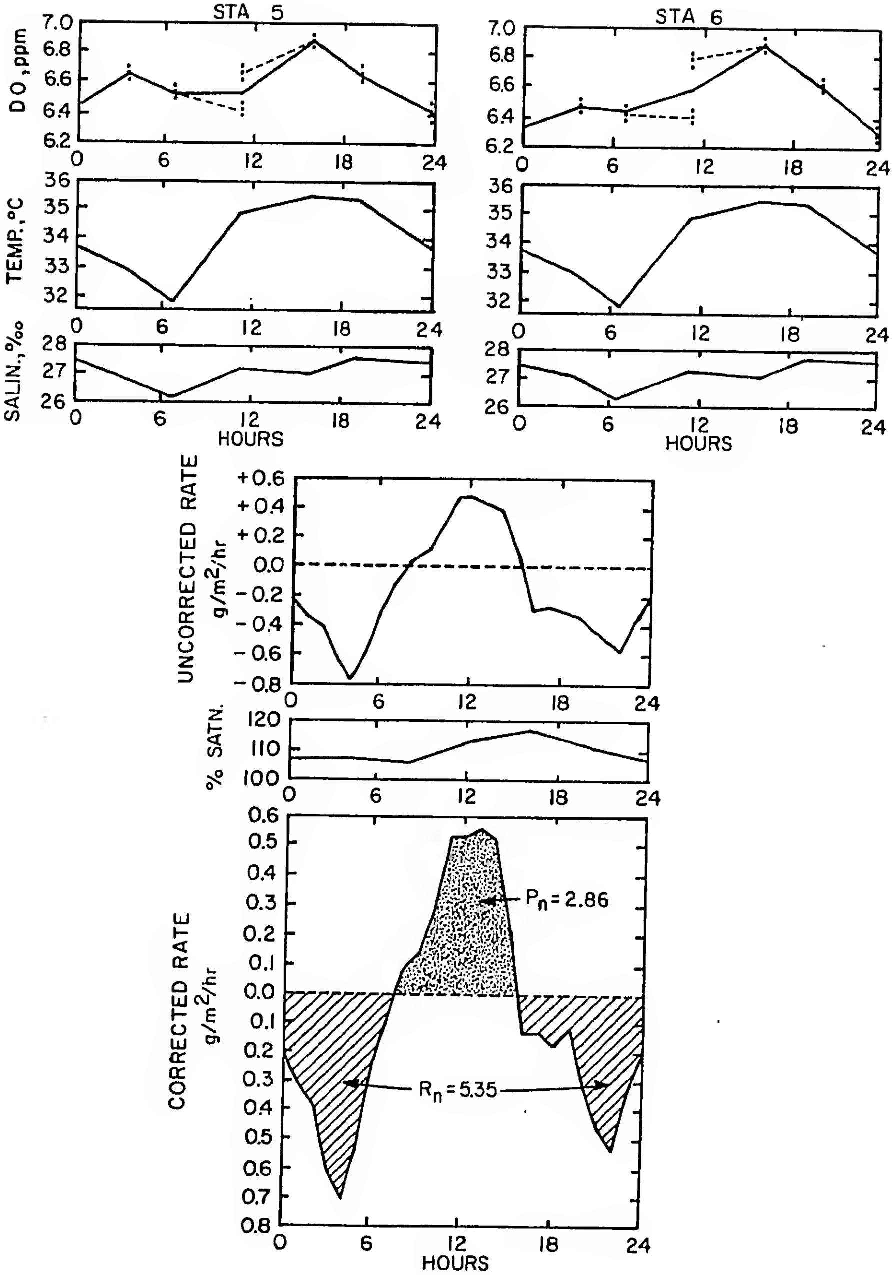

STA 5
STA 6
D O, ppm
7.0
6.8
6.6
6.4
6.2
TEMP., °C
36
35
34
33
32
SALIN., ‰
28
27
26
0
6
12
18
24
HOURS
UNCORRECTED RATE
g/m2/hr
+0.6
+0.4
+0.2
0.0
-0.2
-0.4
-0.6
-0.8
% SATN.
120
110
100
CORRECTED RATE
g/m2/hr
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Pn = 2.86
Rn = 5.35
HOURS

Table 4. Portion of computation table for analysis of rate-of-change of dissolved oxygen between stations 5 and 6 on 1-2 July, 1974, and example calculation corresponding to data given in Fig. 6 and Table 3.*

Upstream		Downstream								Diffusion
t	C_u	$t + \tau$	C_D	ΔC_t, g/m^3	ΔC_t, $g/m^2/hr$	Temp., °C	Salin., o/oo	% Sat'n.	D, $g/m^2/hr$	Corrected $(\Delta C_t/\tau)_c$, $g/m^2/hr$
0	6.64	1.2	6.45	-0.19	-0.77	32.5	26.7	106	+0.06	-0.71
1	6.59	2.2	6.44	-0.15	-0.59					-0.53
2	6.55	3.2	6.46	-0.09	-0.32					-0.24
3	6.53	4.3	6.50	-0.03	-0.11					-0.06
4	6.54	5.5	6.54	+0.01	+0.03	32.3	26.6	105	+0.05	+0.08
5	6.54	6.5	6.57	+0.03	+0.10					+0.14
6	6.54	7.6	6.61	+0.07	+0.24					+0.29
7	6.60	8.5	6.66	+0.12	+0.47					+0.53
8	6.68	9.4	6.72	+0.12	+0.27	35.0	27.1	112	+0.06	+0.53
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮

*Abbreviations in Table are as follows:

t = time of upstream sample; C_u = Dissolved Oxygen (DO) in g/m^3 at upstream station at time, t;
τ = time of flow between stations (see Table M1); C_D = DO in g/m^3 at downstream station at time $t + \tau$;
ΔC_t = change in DO between stations at times t and $t + \tau$, respectively; D = diffusion rate for given

Table 4. (Continued)

temperature, salinity and mean DO between stations, based on diffusion coefficient estimated from current velocity and Fig. 8.

Example calculation for time, $t = 0$

(1) Referring to Fig. 6, find DO at sta. 5 at $t = 0 = 6.64\ g/m^3$ and at sta. 6 at $t + \tau = 1.2$ hr $= 6.45\ g/m^3$,

(2) $\Delta C_t = (6.64 - (6.45) = -0.19\ g/m^3$,

(3) Mean depth, $\overline{Z}$, at 0845 = 4.9 m,

(4) $(\Delta C_t/\tau)\ \overline{Z} = (-0.19\ g/m^3)(4.9\ m)/1.5\ hr = -0.77\ g/m^2/hr$,

(5) At temperature of 32.5°C and salinity of 26.7 o/oo and mean DO of $(C_u + C_D)/2 = 6.55\ g/m^3$, percent saturation is 106 by the formulation of Green and Carritt (1967),

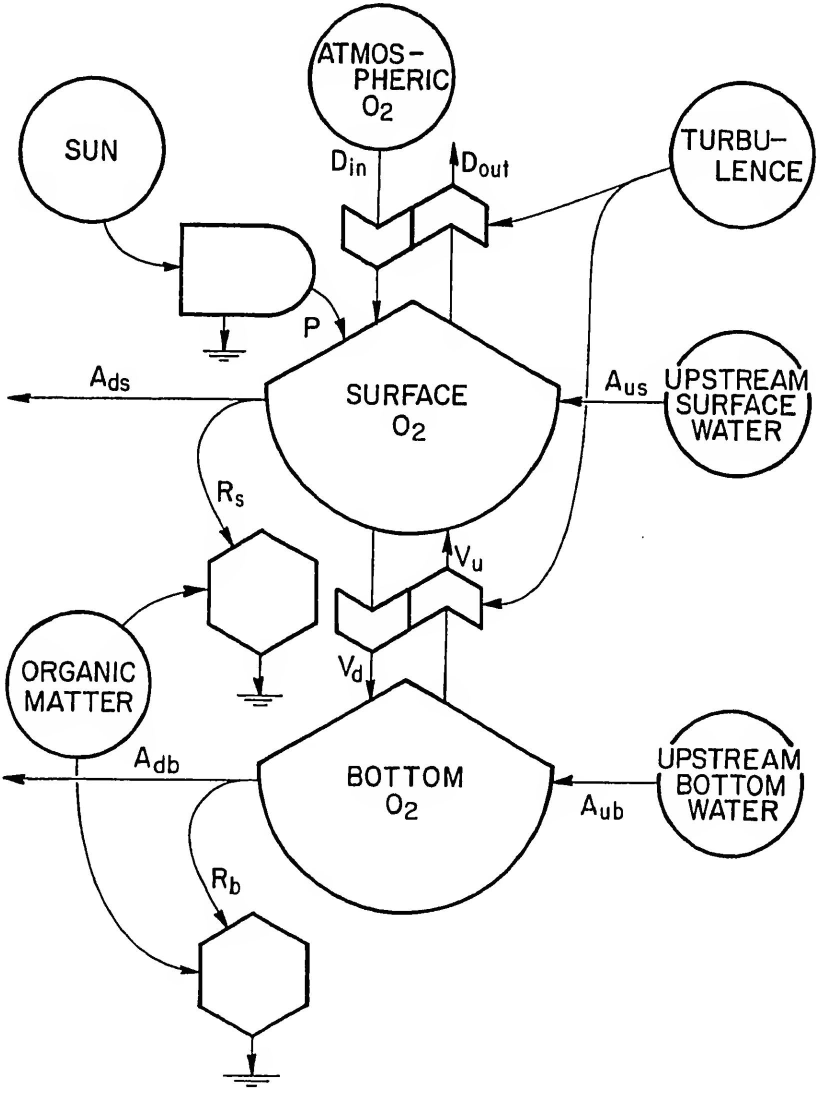
(6) Diffusion, $D = k(100 - \%\ Sat'n.)$ since tide is flooding $k = 0.9\ g/m^2/hr$ per 100% Sat'n. (see eq. (12)), $\therefore\ D = 0.9\ (100-106) = -0.06\ g/m^2/hr$,

(7) Corrected rate-of-change, $(\Delta C_t/\tau)_c = (\Delta C_t/\tau) + D = -0.77 + 0.06 = -0.71\ g/m^2/hr$.

reasonable assumption. Figure 7 illustrates all pertinent processes affecting oxygen content of the two layers.

In the analysis of surface and bottom diurnal oxygen curves, advective, and diffusive oxygen exchange between layers upward (V_u) and downward (V_d) were taken into account indirectly. When the intake canal water column is stratified, these vertical exchanges are relatively small (0.1 - 0.5 g $O_2/m^2 \cdot day$, using vertical diffusivity coefficients of Jassby and Powel, 1975 and Steinberg, 1975); therefore, epilimnion and hypolimnion can be treated as separate water bodies. Under this condition the total community metabolism is simply the sum of the metabolism calculated for the two vertical halves. However, the stratification sometimes breaks down during a diurnal sampling (see description of canal hydrography in "Introduction"). Thus, two new processes, V_d and V_u, enter into the oxygen balance for the upper and lower subsystems. In the surface oxygen compartment of Fig. 7, V_d would appear as additional respiration and V_u as additional photosynthesis, introducing an error. However, an equal but opposite (and therefore compensating) error occurs in the bottom oxygen compartment, where V_d appears as photosynthesis and V_u as added respiration. Therefore, the summation of both surface and bottom metabolism calculations to get total community metabolism is again justified. During the night, the advective exchange of higher oxygen surface water for bottom water with lower oxygen concentrations, if great enough, could appear as spurious photosynthesis in the bottom subsystem and inflated respiration in the upper subsystem. Thus, any positive oxygen changes at night in one layer should be subtracted (algebraically added) from the respiration in the other layer.

Figure 7. Diagram illustrating pertinent processes affecting oxygen concentration in two layers of the intake canal. P is gross photosynthesis; R is total respiration; D is diffusion across the air-water interface; V is vertical eddy diffusion between layers; and A is advection of oxygen as water traverses the canal. Subscripts u and d represent upstream and downstream for advection, and upwards and downwards for vertical eddy diffusion, while s and b designate surface and bottom layers.


ATMOSPHERIC O2
SUN
TURBULENCE
D in
D out
P
A ds
SURFACE O2
A us
UPSTREAM SURFACE WATER
R s
V u
ORGANIC MATTER
V d
A db
BOTTOM O2
UPSTREAM BOTTOM WATER
A ub
R b

Oxygen Diffusion

The process of oxygen diffusing across an air-water interface is driven by the difference in partial pressures exerted by concentrations of oxygen in the water and in the atmosphere. This relationship is given by eq. (11). The diffusion rate coefficient, k, is a function of: temperature; water and air turbulence; and water depth.

Diffusion rate coefficients were measured under several different hydrographic and meteorological conditions using the experimental method of Copeland and Duffer (1964) as modified by Hall (1971) and Day (1971). The method involved measurements of time-changes in oxygen concentration under a plastic dome which floated on the water surface, and which was initially purged of its oxygen content with nitrogen gas. Oxygen concentrations were measured with a Yellow Springs Instrument Model 51-A oxygen probe mounted under the dome and above the water at 10-15 minute intervals for a 1-2 hour duration. The rate of oxygen return at high saturation deficit appeared to be linear as shown by the results from six diffusion experiments in Fig. 8. Diffusion rate coefficients were calculated from this data by the following expression,

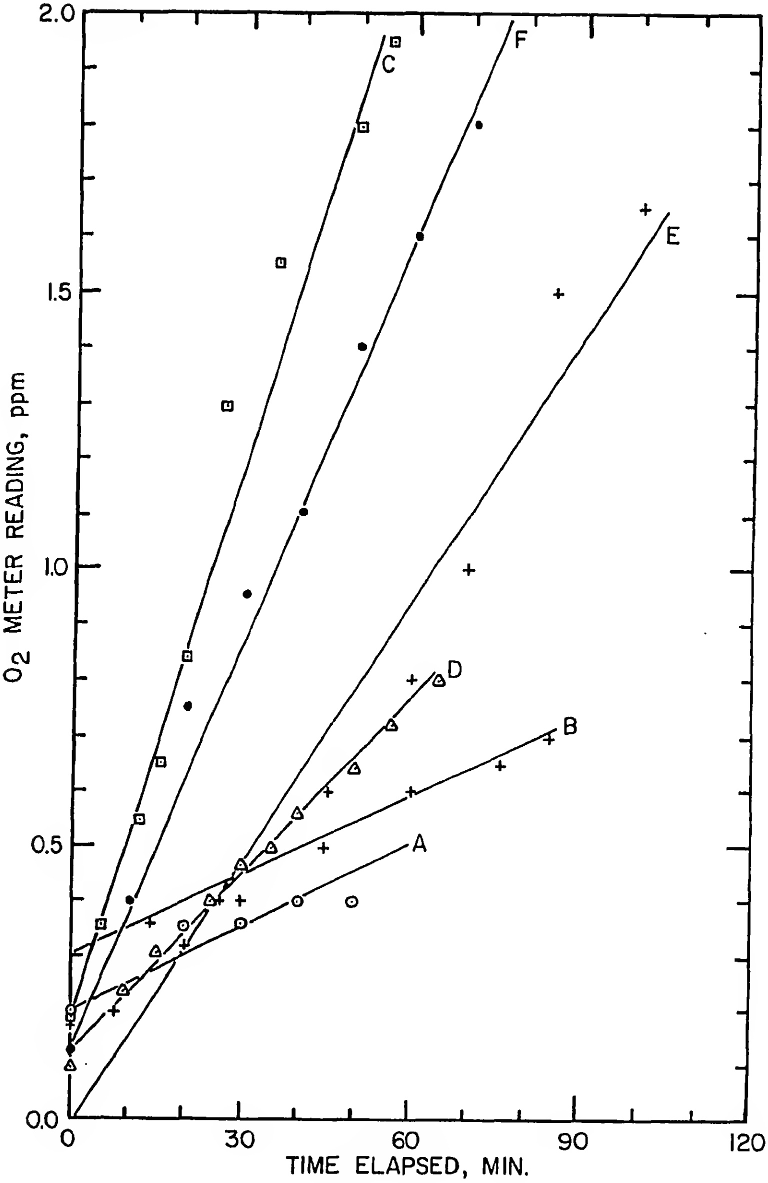
$$k = \frac{(V)(\rho)}{(A)(t)(\text{mean \% sat. def.})} \qquad (12)$$

where k = diffusion rate coefficient in g $O_2/m^2/hr$ at 100% saturation deficit; V = volume of oxygen diffused into the dome; ρ = density of oxygen; A = area of water surface covered by dome; t = duration of experiment; and (mean % sat. def.) = mean percent saturation deficit between water and atmosphere under the dome during the experiment.

Diffusion rates observed for the cooling water canals at Crystal

Figure 8. Oxygen return to a nitrogen-filled plastic dome in experiments to measure oxygen diffusion coefficients (k, g $O_2/m^2/hr$ at 100% saturation deficit). Straight lines, which were fit by inspection, apply only at these high saturation deficits. Data for each experiment given below:

Key	Intake, I or Discharge, D	Date	Wind Speed & Direction kt	Tide	Current, fps	k
A	I	8 Sept 73	5S	High Slack	0.3	0.42
B	I	19 Nov 75	10E	High Slack	0.5	0.44
C	D	8 Sept 73	5SE	Max Ebb	0.65	2.04
D	D	2 Aug 74	20W	High Slack	0.45	0.74
E	D	2 Aug 74	15S	High Slack	0.6	1.02
F	D	19 Nov 75	10N	Max Flood	1.0	1.72


2.0
1.5
1.0
0.5
0.0
0
30
60
90
120
O2 METER READING, ppm
TIME ELAPSED, MIN.
A
B
C
D
E
F

River appeared to be a function of current velocities as indicated by others (O'Connor and Dobbins, 1956; Churchill et al., 1962; Edwards and Owens, 1965; McKellar, 1975). However, direct diffusion measurements made in this study were substantially higher than those predicted by the empirical expressions of these authors. Measurements in the swifter flowing discharge canal were often two or more times as great as in the intake canal. Velocities in the canals vary with tidal phase (see Table 3), being greater in the discharge canal on an ebb tide and in the intake canal on a flood tide. Spoil banks generally shield the waters in both canals from wind effects. However, direct easterly or westerly winds can significantly add to turbulent diffusion, since under these conditions the canal length provides adequate fetch for wind shear. In this study different diffusion rate coefficients were applied for intake and discharge canal systems during tidal ebbs and during tidal floods. Based on data shown in Fig. 8: diffusion coefficients of $k = 0.25$ g $O_2/m^2/hr$ and $k = 0.75$ were used to correct diurnal oxygen curves during ebb and flood tides, respectively, for the intake canal; and diffusion coefficients of $k = 0.9$ and 1.9 were used for the discharge canal under flood and ebb tides, respectively. These coefficients led to diffusion corrections which were generally less than 10% of observed oxygen changes for the intake canal and less than 25% for the discharge canal.

Plankton Metabolism

Net primary production and total respiration of the plankton community were estimated by oxygen changes in light and dark bottles according to the method first described by Gaarder and Gran (1927) and widely used by Riley (1946), Ryther (1956) and others. Standard 300 ml BOD bottles were used with dark bottles painted black and wrapped with grey duct tape. Dark bottle tops were sealed with 2 layers of heavy aluminum foil during experiments. Three sets of three-replicate light bottles and duplicate dark bottles, as well as a pair of initial bottles (to give DO at start of experiment) were filled from a single bucket surface sample with a rubber siphon. Initial bottles were "fixed" in the field and returned to the laboratory for titration. The three sets of light and dark bottles were suspended on chains from floating racks at depths of 0.3 m, 1.5 m, 3.0 m for 24 hrs. It was suggested by Ryther (1956) and Hall and Moll (1975) that 12-15 hr incubation periods be used, primarily to avoid slime growths on internal walls of bottles. However, in marine waters with lower bacterial concentration, this seems less likely a problem than in fresh waters. Numerous researchers, including Odum and Hoskins (1958), Edwards and Owens (1965), Patten and Van Dyne (1968) and Mann et al. (1972) have used diurnal incubations with reasonable success. Metabolism in grams oxygen per m^2 per day was calculated by integrating rates-of-change of oxygen per m^3 over profile to the depth of the euphotic zone which was estimated during dyalight hour of diurnal samples by Secchi disk and submarine photometer.

Sunlight Measurements

Solar insolation was recorded using a Weather Measure Corp. Solar Radiation Recorder Mod. R 401 during the winter and spring of 1974-75. Data was provided by Florida Power Corporation for other dates.

Penetration of sunlight through the water column was determined using Secchi disc readings and a submarine photometer (InterOceans, T.S.

Submarine Illuminance Meter S/N 88/30). Light intensity (illuminance) was measured in the water column and just above the water surface with Nikkon 50 mm filtered lenses at about 0.2 m intervals of water depth from surface to bottom. Two cells were calibrated together on deck and then the underwater cell was lowered into the water to measure percent surface light at various depths. This data plotted on semi-log paper yielded relatively straight lines as shown in Fig. 9, and the light intensity usually decreased exponentially with depth according to the following,

$$I_2 = I_1 e^{-K(z_2 - z_1)} \tag{13}$$

so that,

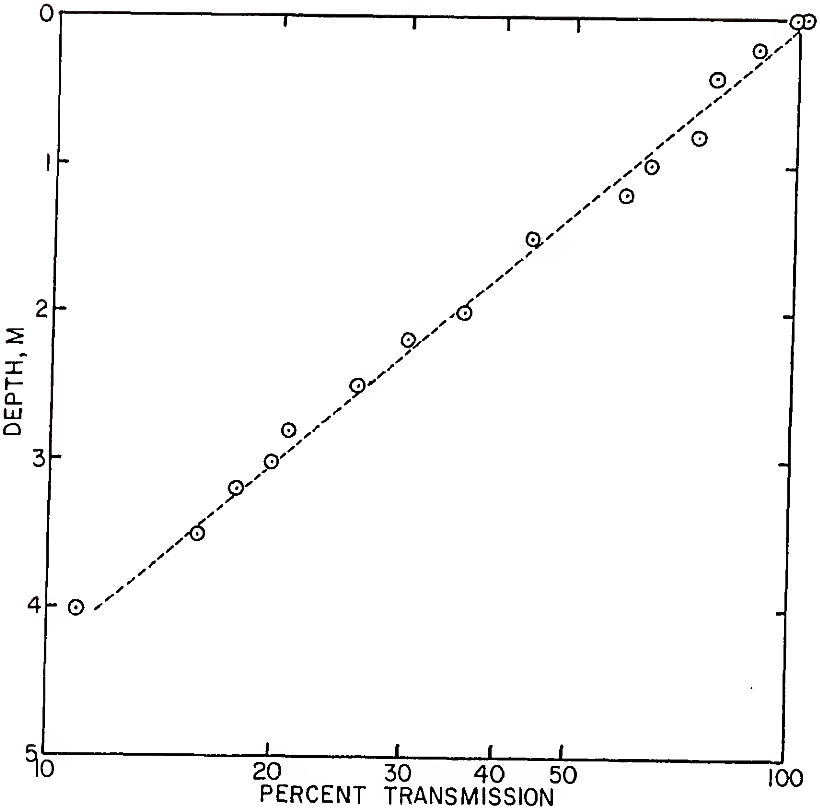
$$K = \frac{\ln (I_1/I_2)}{z_2 - z_1} \tag{14}$$

where I_2 is the light intensity at a lower depth, z_2; I_1 is the light intensity at an upper depth, z_1; and K is extinction coefficient.

Benthic Community Structure

Littoral and shallow subtidal benthic animal community structure in the canals was studied by measuring abundance, biomass and species diversity. Relatively homogeneous sampling areas were established for both canal ecosystems (Fig. 4) and were marked-off with stakes at 5 m intervals for 50-60 m along the mean-low-water (MLW) mark. Each square-meter quadrat was assigned a number, and the quadrat to be sampled on a given date was selected randomly. Within the designated 1 m^2 quadrat, a 0.25 m^2 frame was placed so as to obtain a representative sample of that quadrat.

Figure 9. Example of light penetration data measured with submarine photometer on 19 Nov. 1975 at Sta. 6 in the vertically well-mixed discharge canal.


0
1
2
3
4
5
DEPTH, M
10
20
30
40
50
100
PERCENT TRANSMISSION

All substrate and organisms inside the frame were collected to a depth of about 15 cm below the sediment surface or to the zone of black anaerobic mud, and were returned to the laboratory for sorting. Samples were washed onto a 2 mm mesh screen to retain those animals defined as the macrofauna, which typically comprise greater than 90% of the total benthic faunal biomass (Thorson, 1966). The occurrance and abundance of all animals was recorded, and organisms were blotted, weighed and then dried to constant weight at 32°C (90°F) (Lehman, 1975). Blotted wet and dry weights were recorded along with the total number of macrofaunal species encountered in the 0.25 m^2 sample. To make samples with different total numbers of individuals comparable, the number of species which would have been found if just 1000 individuals had been counted in each sample was calculated. This was done assuming that $S = c \log N$, where S is the number of species in the sample, N is the total number of individuals sampled and c (slope of logarithmic plot of S vs. N) is a coefficient of diversity (Odum et al., 1960).

Early in the study, several bottom samples (obtained with Peterson and Ekman dredges), as well as SCUBA observations and hand-cores, indicated that the animal community in the mud at the bottom of canal channels was very sparse (each of 24 samples gave biomass < 1 g organic matter/m^2).

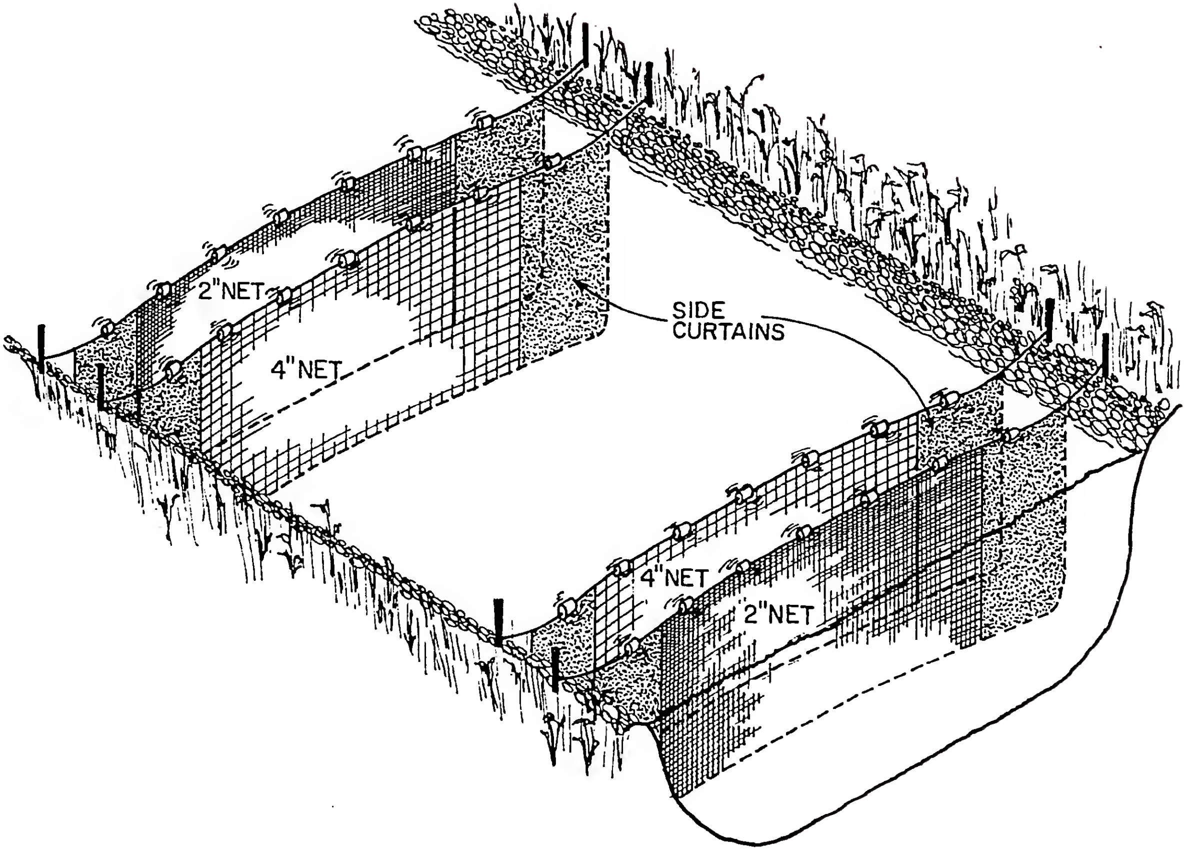
Nekton Sampling

The actively swimming pelagic nekton, as well as some demersal fish were sampled on two occasions (19-20 March and 24-25 June, 1975) by overnight gill-netting. Designated areas (about 5500 m^2) in each canal were enclosed by combinations of 5.1 and 10.2 cm (2 and 4 in) multi-filament nylon stretch-mesh gill nets secured at ends on steel (re-enforcing bar) stakes (see Fig. 10). Additional nets were set across the western ends of the laterally-confined part of both canals to monitor fish movements into and out from the ecosystems. After the nets were payed-out and secured, outboard motorboats were run back-and-forth within the enclosed areas and immediately outside the nets and paddles were knocked against the hull of the boats in effort to create movement among the entrapped fish to drive them into the nets. Nets were set shortly after sunset and retrieved shortly after daybreak, and netted fish were removed periodically throughout the night. Fish were sorted according to the net on which they were caught and the direction in which they were moving, and were identified, counted, measured for standard length (SL) and weight in the laboratory.

Population density of the polkadot batfish, Ogcocephalus radiatus, in the intake canal was estimated for the fall of 1973 in two ways: (1) mark-recapture; (2) SCUBA census. SCUBA counts and tagging of these fish were done by Dorman and Sutton (1973), and their unpublished data were analyzed in the present study for estimates of abundance and biomass. The mark-recapture study was done over an 11 day sampling period in September 1973. A total of 306 fish were tagged on the north spoil bank of the intake canal, while 77 were tagged on the south bank, and 8 tags were recovered, all from the north bank. The SCUBA surveys were done along twenty-four 50 m transects across and along the canal. In each case, a 2 m wide swath was observed so that a transect sampled an area of about 100 m^2. Thirteen transects were also observed along the bottom of open bay waters near the intake canal for comparison.

Mark-recapture data were interpreted for estimates of nekton

Figure 10. Illustration of gill net placement for fish sampling in the canal ecosystem. Diagram was adapted from a drawing in Nugent (1970).


2"NET
4"NET
SIDE CURTAINS
4"NET
2"NET

populations (N) using the Peterson equation (Ricker, 1968):

$$N = \frac{m \cdot c}{r} \qquad (15)$$

where c = number of captures, m = number marked, and r = number of recaptures. The validity of this equation rests on the following assumptions (Royce, 1972): (1) that marked organisms are randomly dispersed among the population; (2) that the number of marked animals does not disproportionately decrease due to death caused by marking or loss of mark; (3) that marked and unmarked organisms are equally susceptible to capture; (4) that the study population does not significantly increase due to recruitment; and (5) that marked nekton do not emigrate from the study area.

Population estimates were also made for blue crabs, Calinectes sapidus, in the intake canal using the tagging data of Oesterling (1973, 1976; Adams et al., 1974). Oesterling's tag returns indicate that there was substantial movement of blue crabs through his study area. In view of assumption number 5 (above) it was necessary to modify the Peterson formula to account for migration in order to calculate crab populations from Oesterling's tagging data. The derivation of this modified equation is given in Appendix D, and the resulting formula is as follows:

$$N_c = \frac{c_c}{r_c} \left[m_c + r_{cn} \left(\frac{m_c}{r_c} + 1 \right) - r_{bn} \left(\frac{m_b}{r_b} + 1 \right) - J_{ms} \right] , \qquad (16)$$

where: N_c = population estimate in the canal; c_c = number of crabs caught in canal; r_c = number of crabs recaptured in the canal; m_c = number of crabs marked in the canal; r_b = number of crabs recaptured in the bay; m_b = number of crabs marked in bay; r_{cn} = number of crabs marked outside the canal and recaptured in canal; r_{bn} = number of crabs marked in canal and recaptured outside canal; and J_{ms} = number of crabs marked in canal and impinged on plant screens.

Total immigration to, and emigration from, the canal's crab population were also estimated by assuming the following proportionalities:

$$J_{Nb} = J_{mb}\ (N_c/m_c) \qquad (17)$$

$$J_{bN} = J_{bm}\ (N_b/m_b) \qquad (18)$$

where J_{Nb} is total emigration, J_{bN} is total immigration and other terms are as previously defined. In general the mark-recapture methods for population estimates tend to be negatively biased; however, as long as $r_c \geq 7$ this bias will be negligible (Robson and Regier, 1968). The standard error (S.E.) of $\hat{N}_c$ may be calculated by the following equation from DeLury (1951) and Robson and Regier (1968):

$$\text{S.E.} = \hat{N}_c \sqrt{\frac{(\hat{N}_c - m)(\hat{N} - C)}{mc(\hat{N}_c - 1)}} \quad . \qquad (19)$$

Monthly mark-recapture data were used to generate cumulative estimates of population using a Schnabel-type estimate (Royce, 1972) where,

$$N_c = \sum (m_c\ c_c)/\sum r_c \quad . \qquad (20)$$

Calculations of Energy Cost

Energy cost calculations were made in this study to estimate the load placed by economic investments on regional energy resources and the effects of economic activities on the environment. For the purposes of this study "energy cost value" is defined as the total energy used from the combined economy of man and nature, where all energies are expressed in units of the same quality (H.T. Odum, 1971, 1976). Calculations were made to quantify the work contributions from various components of a coastal region which includes cities, power plants, agriculture, forests and estuaries.

By definition all work processes involve flows of energy; it is the presence of potential energy that enables work to be done. Since flows of matter and information both carry energy, equivalent energy units are most appropriate to serve as a common denominator in analysis of the complex systems of man and nature (H.T. Odum, 1971). Energy (expressed in equivalent terms) was used here to measure the value of work done by natural ecosystems and by man. In human economies, money and energy (goods, services, fuels, etc.) flow couter-current to one another (Odum, 1967), and the ratio of the total U.S. fuel consumption (F) plus natural energy input in equivalent units (N) to its GNP gives a relationship of energy to dollars within the general U.S. economy (approximately 20,000 kcal/$ in 1974: Kylstra, 1974; Kylstra and Han, 1975). This ratio was used to convert dollar value to energy value for goods and services imported from the general U.S. economy into the study area. Energy to dollar ratios for other national economies (used in desalination and tidal power computations) were calculated from data given in Darmstadter et al. (1971).

Expressing Energy in Units of Same Quality

Energy quality ratios have been used by Odum (1974b) to indicate relative energy transformation costs of various kinds of energy as a possible measure of ability of energy to do work. These ratios (R) can be used to convert each type of energy involved in a quantitative evaluation into a base energy quality such as that of coal (Odum, 1973, 1974b). Thus, the energy quality ratio between two kinds of energy flow is the ratio of the amount of one type used to generate a unit amount of the other. The energy quality ratio (R_i) for a given energy type (E_i) compared to coal (E_c) is given as follows:

$$R_i = E_c/E_i \quad . \tag{21}$$

The energy value (V_i) of an energy flow is then equal to the Caloric value multiplied times the energy quality ratio (R_i) and is given in terms of coal equivalent Calories (Kcal CE),

$$V_i = R_i \cdot E_i \quad . \tag{22}$$

The United Nations, the U.S. Federal Power Commission and others, as a matter of convenience (and perhaps recognizing this energy quality concept), have adopted the convention of reporting energy resource data in "coal equivalent" units. Thus hydropower, natural gas, fuel oil and coal can all be compared on the common basis of ability to generate electricity, and the significance of this convention in resource planning is indicated by Darmstadter et al. (1971). Moreover, in a brief letter to Science, Alter (1975) argued for a consistent format in the use of energy equivalents. Coal equivalents (CE) are also used in the present study as the basis for energy quality ratios and energy value calculations. A complete listing of all energy quality ratios used in this study is given in Table 5. Estimates of quality ratios for waves,

Table 5. Energy quality ratios used to compare various kinds of energy in terms of their ability to do work. All ratios stated relative to the quality of coal (coal equivalents).

Type of Energy	Energy Quality Ratio kcal per kcal Coal
Incident solar ratiation[a]	0.0005
Mean gross primary productivity[a]	0.05
Atmospheric wind[b]	0.1
Waves on Florida coast[c]	1.2
Tides at La Rance, France[d]	1.5
Hydrostatic head[e]	1.7
Chemical potential of freshwater[f]	3.1
Electricity[g]	3.6
Estuarine animal production[h]	
Herbivore, detritivore (Striped mullet)	1.2
Top Carnivore (Crevalle jack)	14.9

[a] Calculation based on sunlight needed to grow trees, needed to generate electricity via steam turbine (Odum, 1974b) and on electric current generated from redox potential by blue green algal mat (Odum and Kylstra, 1976).

[b] Estimate based on solar ratiation needed to generate winds in the earth's atmosphere (Kemp and Boynton, 1974).

[c] Calculation based on sediment transport accomplished by coastal waves.

[d] Calculation based on electricity generated at tidal power plant with 7.4 m tidal range.

[e] Based on electricity generated at a hydroelectric power plant (Boynton, 1975).

[f] Estimate based on energy needed for desalination for arid and insular regions.

[g] Based on electricity generated at a coal-fired steam electric power plant (Odum, 1974b).

Table 5. (Continued)

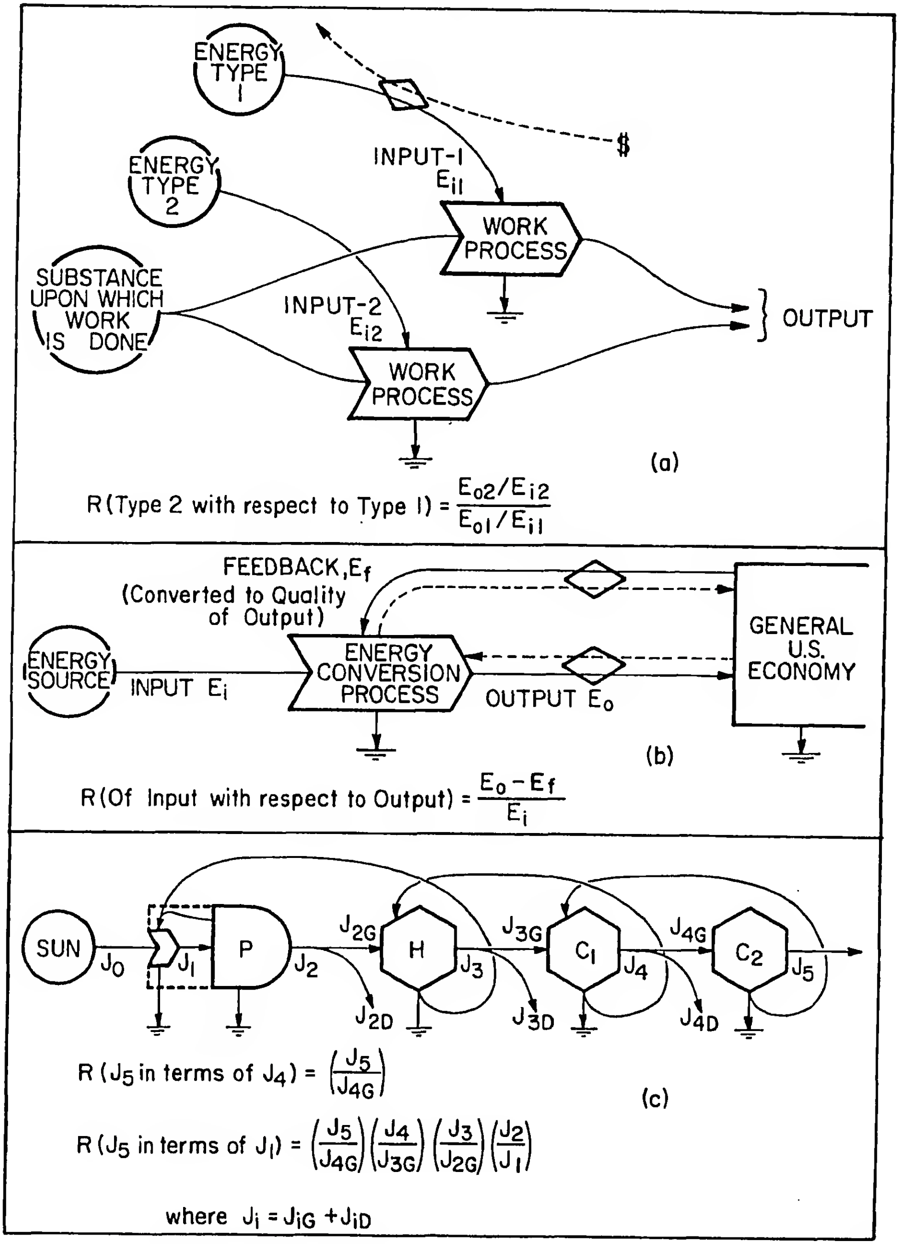
[h] Calculation based on amount of gross primary production needed to support production of animals where "top carnivore" function is defined to feed exclusively on mid carnivores which feed exclusively on first carnivores which feed exclusively on herbivores in estuarine food webs.

tides, freshwater and metabolism of estuarine animals are developed in this dissertation while the others are from previous reports (Odum et al., 1975; Odum and Brown, 1975; Boynton, 1975; Zucchetto, 1975b).

Energy quality ratios were calculated empirically by examining work processes where there was interaction between an energy flow of known (or base) quality and an energy flow of unknown quality. The relationship between these two kinds of energy was quantitatively described, so that the energy quality of the two energies could be compared. The methods assume that the systems under study had been exposed sufficiently to competition and therefore had been adapted to minimize waste and maximize use of these energies. Under these assumptions, the cost of generating a unit of a given energy form would be equal to the work which could be effected by that same unit of energy (Odum, 1976). Three techniques used in this study are depicted in Fig. 11. In the first method (Fig. 11a) two different kinds of energy which are able to accomplish the same work output are compared in terms of the heat equivalent energy needed by each to achieve the same end. In this case energy quality ratios are calculated in terms of work effect of a given energy unit. When data for direct energy use were not available, the energy involvement for a fossil-fuel-based process was estimated by the associated dollar costs for that energy, using an energy dollar conversion factor estimated for the general economy or for a particular sector of the economy.

In the second method (Fig. 11b) inputs and outputs of a work process through which energy of unknown quality is converted to energy of known quality are examined to compare the two types of energy. The net output of the process is calculated by subtracting from the gross

Figure 11. Diagrams showing three methods for calculating energy quality ratios. (a) Comparison of two different kinds of energy used to accomplish the same work output by means of two different pathways. (b) Analysis of energy conversion process, where the subsidy of goods and services from general economy are subtracted from gross process output to obtain the energy used in generating net output. (c) Energy quality upgrading along a hypothetical food-chain system, where P = plants, H = herbivores, C_1 = primary carnivores, and C_2 = secondary carnivores. Note the multiple feedback flows which amplify the upgrading processes.



$$R(\text{Type 2 with respect to Type 1}) = \frac{E_{o2}/E_{i2}}{E_{o1}/E_{i1}}$$

$$R(\text{Of Input with respect to Output}) = \frac{E_o - E_f}{E_i}$$

$$R(J_5 \text{ in terms of } J_4) = \left(\frac{J_5}{J_{4G}}\right)$$

$$R(J_5 \text{ in terms of } J_1) = \left(\frac{J_5}{J_{4G}}\right)\left(\frac{J_4}{J_{3G}}\right)\left(\frac{J_3}{J_{2G}}\right)\left(\frac{J_2}{J_1}\right)$$

where $J_i = J_{iG} + J_{iD}$

energy output, E_o, the energy (in quality units of the output) fedback from the economy to support the process, E_f. In this case energy quality ratios are calculated in terms of energy cost needed to generate a unit of a given energy form. Data for this feedback, which consists of goods and services needed to keep the process functioning, is often available only in monetary "operating cost" figures which can be converted, as before, to coal equivalent energy units using an appropriate energy:dollar ratio for U.S. economy. The energy quality ratio for the input energy (E_i) is then,

$$R_i = (E_o - E_f)/E_i \quad . \tag{23}$$

The energy quality of the metabolism of various estuarine organisms was calculated by developing food-web models of an estuarine ecosystem (Fig. 11c). Data on standing stock, production, respiration and diet of organisms part of the saltmarsh creek ecosystems at Crystal River were provided primarily by Homer (1974, 1976), Young (1974b), Evink and Green (1974) and Carr and Adams (1973). A few data (e.g., assimilation rates), not available specifically for Crystal River, were obtained from the general scientific literature for similar organisms or ecosystems.

A detailed quantitative model of the trophic system was then developed to investigate the energy quality ratio for work done by higher organisms, by calculating the amount of gross primary productivity needed to support a unit of secondary production at a given level (effect). This detailed model was then generalized into a trophic-function model similar to that shown in Fig. 11c with organisms apportioned into appropriated trophic groups according to dietary data. This generalized model was characterized by 9 distinct heterotrophic feeding levels organized along two branches, from herbivore to third carnivore, and from detritus to third carnivore.

The method of apportionment is identical to that described by Kemp et al. (1974) and later refined by Homer and Kemp (1976). It was done by calculating the portion of each organism's diet that corresponds to each of the trophic levels shown in Fig. 11c. Thus, for example it was found that the trophic habits of the tidewater silverside, Menidia beryllina, in a saltmarsh creek ecosystem at Crystal River was comprised of 55% benthic microinvertebrates, 38% zooplankton and 6.3% detritus. Silversides therefore function as first carnivores in the detritus branch (detritus, level II) via two pathways: (1) plants → detritus → benthic microinvertebrates → silversides; and (2) plants → detritus → copepods → silversides. It was assumed that benthic microinvertebrates feed almost entirely on detritus, and zooplankton are about 75% detritivores so that the partial-feeding coefficient (as termed by Riley, 1966) for silversides at this trophic level is

$$A_{ik} = \sum_{j} \prod_{k-1} a_{ij} \qquad (24)$$

where i designates predator species, j indicates prey species and k designates trophic level, and a is fraction of predator's (i) diet comprised by prey (j). Standing stocks and metabolic rates of each organism were apportioned to the general trophic levels (according to these partial-feeding coefficients) to produce the generalized model.

Energy quality ratios were then calculated for all trophic levels of the generalized model assuming that each trophic group upgrades the energy which it processes in proportion to the ratio of input (consumption) to output (production). This is analogous to the energy upgrading which takes place in a steam electric power plant as input (coal) is converted to output (electricity). This ratio of input to output, which has been termed "ecological growth efficiency" by Odum (1957) and categorized "EE4-0" by Kozlovsky (1968), is about 3.6 for a coal-fired power plant (Odum, 1974b) and ranges from 1.43-10.0 for the general trophic web developed in this study. Thus, in the example food chain of Fig. 11c, the energy quality ratio for a top carnivore's production compared to gross primary productivity is simply,

$$R = \left[\frac{J_2}{J_{46}}\right] \left[\frac{J_4}{J_{36}}\right] \left[\frac{J_3}{J_{26}}\right] \left[\frac{J_2}{J_1}\right] \quad . \qquad (25)$$

Once these energy quality ratios are calculated for each of the general trophic functions, the energy quality of any organism can be estimated by determining the portion of its feeding characteristics which corresponds to each of these general trophic levels (i.e., to what extent is it a herbivore, detritivore, first carnivore, etc.). The generalized trophic model then permits approximate calculations for the energy quality of organisms not found in the saltmarsh creek ecosystem for which the food web was developed, but found in similar systems (as long as their trophic habits were known). This calculation then attempts to put the value of higher trophic level organisms of an ecosystem into proper perspective according to their energy role in the ecosystem.

Regional Maps and Energy Evaluations

The ratio of fossil fuel energies used in a region to the natural, renewable energies in that region was defined as the investment ratio (Odum and Brown, 1975). This ratio can serve as a relative index of the inherent ability of a region to attract further fossil-fuel-based investment and for the ability of such investment to return competitive benefits (Odum and Kylstra, 1976). Underdeveloped regions (low ratio) may be less competitive because they do not make full use of their energy potentials, while overdeveloped regions (high ratio) are less competitive because they must sell their product goods and services at higher prices than regions with a balanced energy economy (Odum and Odum, 1976).

In this study the relative balance between natural and fossil fuel energies was determined for the powershed by compiling energy data for 1973 into a regional energy budget. The major inputs of material, money and energy to the powershed were estimated from analysis of fuel and economic data for 1973 (from various sources including: BEBR, 1975, FEDC, 1975a, b; NOAA, 1973; Shrode et al., 1975). Where possible data were assembled on a county by county basis, so that some 32 pieces of information (one per county) were used to estimate a single flow. Seven of the 32 counties (Alachua, Columbia, Jackson, Liberty, Polk, Seminole and Volusia) are only partially included within the powershed boundaries, and data for these were prorated on the basis of the fraction of total county population contained in the powershed. An ecosystem map of the region was developed from ERTS infrared imagery, combined with soil maps and ground-truth information and using a general vegetation map of J.H. Davis (1967). Values for gross primary production (annual means) per unit area of each ecosystem type were adapted from the scientific literature (see Table 6). These rates were multiplied by respective areas of coverage for each ecosystem classification to estimate total ecological production in the region. Considerable variability exists in these data (e.g., Westlake, 1963 and Bayley and Burns, 1974 for freshwater marshes); however, the numbers used represent a synthesis of the best available information.

Contributions of other natural energies to the regional budget were estimated from climatologic, hydrologic, and hydrographic data. A diagram of rainfall and topographic isopleths in the region was developed (NOAA, 1971 for rain, Raisz and Dunkle, 1964 for topography) by interpolating rainfall measurements at 31 rain-gauge stations spaced throughout the region. The region was thus broken into sectors outlined by intersections of rainfall isopleths with topographic lines. The total hydrostatic head (P_{RH}) in the region (potential of elevated water) was then calculated as the summation of hydrostatic head in each sector:

$$P_{RH} = \rho g \sum_{i} \sum_{j} Q_i h_j \qquad (26)$$

where ρ is the density of water, g is the acceleration of gravity, Q_i is the total runoff and infiltration between isohyetals i and i-1, and h_j is the mean elevation of water above sealevel between topo-lines j and j-1. Streamflow data (McNulty et al., 1972) on gauged rivers (Apalachicola R., Ochlockonee R., Aucilla R., Suwannee R. and Withlacoochee R.) were used in conjunction with rainfall data for small or ill-defined coastal watersheds to calculate the chemical potential (free energy, ΔG) of freshwater with respect to the sea (H.T. Odum, 1970). Runoff coefficients from G.G. Parker (1974) were used to estimate the portion of rainfall not evapo-transpired back to the atmosphere.

Isopleths were interpolated from mean wind speeds measured at 10 weather stations in the region to aid in calculating an average (area-weighted) wind energy (NOAA, 1955-1971). Mean annual tidal ranges were calculated from tide predictions of NOAA (1973) for 43 points along the region's Gulf Coast. Wave roses estimated from ship and shore observations (Walton, 1973), were used to calculate the mean wave height (and energy) along the Gulf Coast, and these data were further used to determine an area-weighted average input of wave energy to the region.

Energy Value of Estuarine Ecosystems

The value of estuarine ecosystems and their organisms was calculated by examining their associated energy flows in coal equivalent units. The impact of power plant operation on the estuary was determined by estimating changes in these energy flows attributable to the power plant. For meroplankton (larvae of larger organisms) three kinds of energy value were considered: (1) value to ecosystem as plankton; (2) to ecosystem as adults; (3) directly to man's economy as food, game and industry. Adding these three values introduces little if any double-counting error. The few plankters that survive to adulthood are counted both as plankton and adults, but, in fact, they function in both roles. In many fisheries only well-matured organisms can be harvested and, thus, the mature of the species may function in the ecosystem as adults for years before being taken directly into man's economy. When this is the case the adult fish generate both values 2 and 3 (above) to the regional system.

Holoplankton (zooplankters throughout their life cycle) were considered to have only the first of the above energy value characteristics and this was calculated as follows:

$$\dot{E}_P = \sum_i C\cdot Q\cdot \partial\cdot m_P\cdot V_{mP}\cdot \tau_P\,(r_P - r_D) \tag{27}$$

where,

C = concentration of plankton at plant intake (ind/m^3)

Q = plant cooling water flow (m^3/yr)

∂ = mortality proportion (ind killed/total ind)

m_P = specific biomass (g/ind)

V_{mP} = specific production (kcal/g-yr)

τ_P = production time constant -- biomass/production rate (yr)

r_P = energy quality ratio for plankton production

r_D = energy quality ratio for detritus (kcal coal/kcal detritus)

i = species designation

Notice that the value as detritus is subtracted from the value as plankton, since even dead organisms have ecological value.

The two other energy values of meroplankton in the regional system as indicated above can also be calculated. Meroplankton have two other calculable values (in addition to that indicated by Eq. (27)) in the regional system. Besides their importance ot the ecosystem as plankton, they have the additional ecological energy value as adults if and when they achieve maturity. The magnitude of the loss of meroplankton as potential adults can be calculated as follows:

$$E_A = \sum_i C\cdot Q\cdot \partial\cdot S_A\cdot m_A\cdot V_{mA}\cdot \tau_A\cdot r_A \tag{28}$$

where,

C, Q, ∂, i = same as for equation (27)

S_A = natural survival rate to adulthood (no. adults/no. juveniles)

m_A = specific adult biomass (g/ind)

V_{mA} = specific production for adults (kcal/g-yr)

τ_A = production time constant (yr)

r_A = energy quality ratio for adults (kcal coal/kcal adult production)

The natural survival rate, S_A, for eggs is simply the fecundity (total number of offspring per female lifetime) divided by two adults. For larvae S_A is calculated as 2/[(fecundity)(S_L, survival rate from egg to larvae)]. For marine organisms S_L can be assumed to be equal to 0.25 (AEC, 1973a).

Furthermore, some adult organisms emerging from meroplankters have special economic value to man as commercial and game fish (such as oysters, shrimp, menhaden, mullet, seatrout, and tarpon). This economic value is determined by supply and demand factors in the market system, and it was calculated in this study as follows:

$$E_D = \sum_i C \cdot Q \cdot \partial \cdot S_A \cdot m_A \cdot d \cdot r_d \qquad (29)$$

where,

C, Q, ∂, S_A, m_A = same as for equation (28)

d = monetary value of adult (\$/g)

r_d = ratio of energy to money in U.S. economy (kcal coal equivalent, CE/\$ GNP)

Monetary values (prices) of adult organisms are taken as "dockside values" to avoid including other economic inputs to the final product as if they were part of the inherent fisher value.

Many juvenile fish are former meroplankton which have survived the rigors of larval stages, and they also represent three kinds of energy value (as above) which can be computed. The survival rate from juvenile stage to adulthood is greater than from larval plankton to adulthood. This survival rate can be calculated more specifically for juveniles as follows:

$$F/f = e^{\left[\frac{-\ln(f/2)\,t}{a}\right]} \qquad (30)$$

where,

$$S_j = (2/f)e^{\left[\frac{\ln(f/2)\,t_j}{a}\right]} \qquad (31)$$

F = no. surviving progeny at time, t

f = fecundity, or F at t_o (spawn)

2 = number of adults surviving from initial spawn

a = age of sexual maturity, years

t = time, years

S_j = survival rate from juvenile stage, j

t_j = age of juvenile stage, j

Equation (30) expresses an exponential mortality rate (Ricker, 1968) between the time of hatch and that of sexual maturity, and it assumes that natural survival is a density-dependent process. The survival rate for given juvenile stage (j) is then calculated with equation (31), assuming that 2 adult offspring arise from a single spawn. While this method overlooks non-density-dependent factors affecting mortality, it is more specific than the general assumption of a constant percent survival from egg to larvae.

Adult organisms have energy value associated with the work which they do in the estuarine ecosystem. Certain of these higher organisms also have economic (and energy) value to the regional system in man's fisheries. The energy value of nekton which were impinged and killed at the power plant intake was calculated as follows:

$$E_A = \sum_i \gamma_i \cdot M \cdot \partial \cdot (r_A - r_D) \tag{32}$$

where,

∂, i, r_A, r_D = same as equation (27)

γ_i = percent total composition comprised by species, i

M = total biomass entrapped

The potential economic value lost from impingement mortality of nekton was estimated for the study region using the following equation:

$$E_D = \sum_i \gamma_i \cdot M \cdot \partial \cdot d \cdot r_D \tag{33}$$

where,

γ, i, ∂, M = same as equation (32)

d, r_D = same as equation (27)

Similarly, the effects of power plant waste discharges on estuarine ecosystems was estimated as the change in energy flow in those ecosystems (given as coal equivalents). Gross primary productivity was assumed to be a measure of the integrated work done by estuarine ecosystems, and the power plant impact was estimated from the following expression:

$$E_M = \sum_k P_G \cdot \partial_M \cdot A \cdot r_M \tag{34}$$

where,

P_G = gross primary productivity of subsystem

∂_M = fraction effect on metabolism

A = affected area, m^2

r_M = energy quality ratio

k = subsystem designation.

RESULTS

The results of this study are organized into six sections, dealing with: (1) energy analysis of powershed region; (2) ecological effects of power plant; (3) costs of alternative cooling systems; (4) field measurements of canal ecosystems; (5) quality of natural energies; and (6) simulation of an estuarine ecosystem model.

Energy Analysis of Powershed Region

An energy budget has been calculated for the regional system (powershed) which interacts with the Crystal River power plant. The purpose of this section is to put the power plant in a macroscopic perspective by examining energies which support it. Figure 12 depicts the main inputs and outputs of energy, information, matter and money associated with the powershed. Both the free, renewable energies of nature and purchased fossil-fuel-based energies are included.

Energy and Land-Use Maps

The spatial character of natural energy inputs to the study region is shown in Figs. 13-16. In Fig. 13 patterns of terrestrial vegetation and land use are shown for 1973. Two categories of urban land use, four agricultural categories, and twelve categories of natural ecosystems were used. A full-size version of this vegetation map is given in the pocket-flap at the back of this report. Another four mixed vegetation

Figure 12. Energy diagram of regional study area (powershed of Florida Power Corporation) depicting energy and economic budgets.

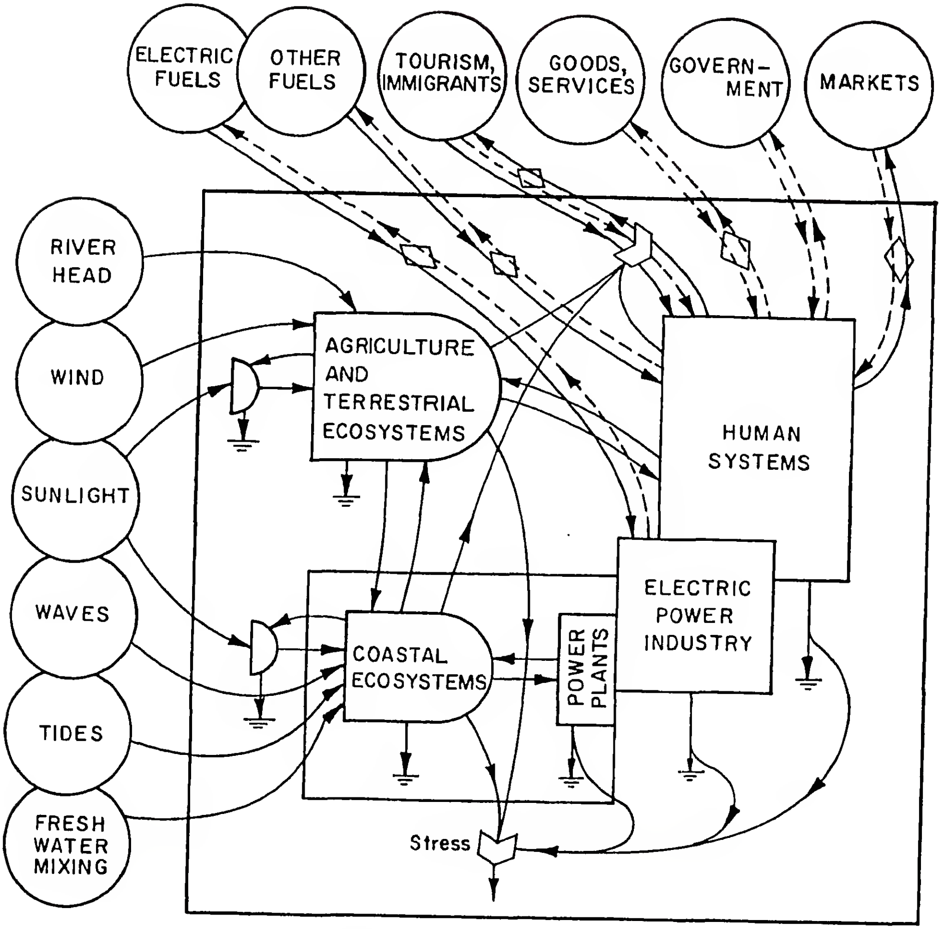
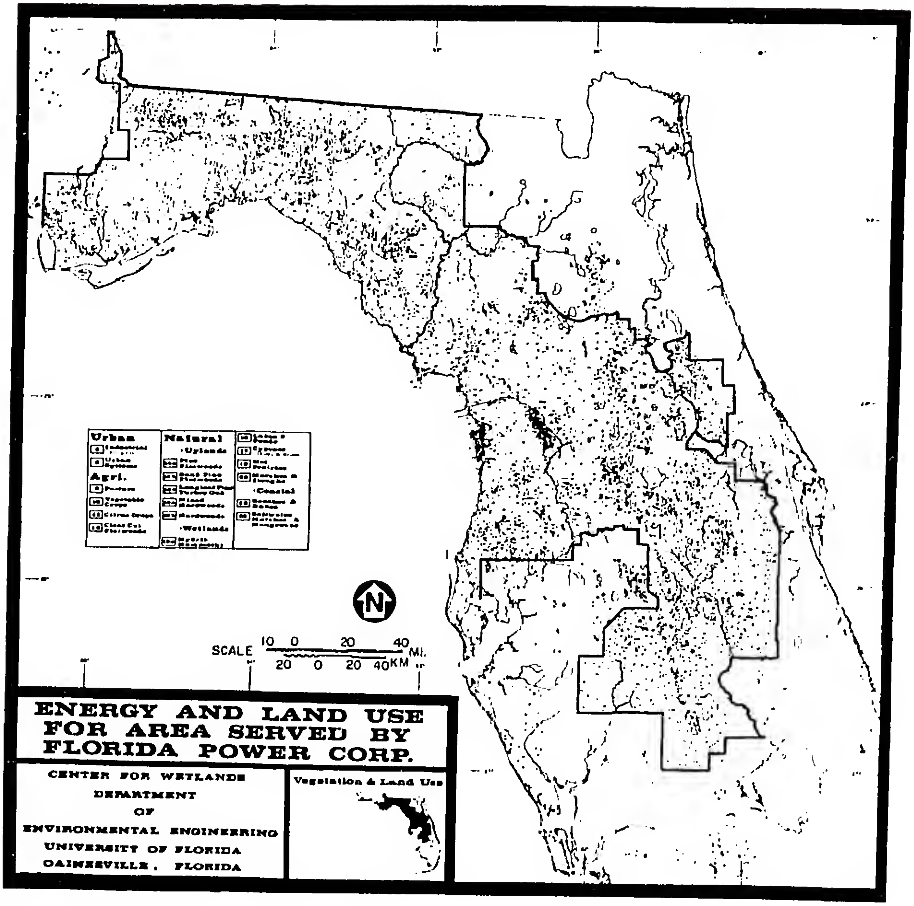

ELECTRIC FUELS
OTHER FUELS
TOURISM, IMMIGRANTS
GOODS, SERVICES
GOVERN-MENT
MARKETS
RIVER HEAD
WIND
SUNLIGHT
WAVES
TIDES
FRESH WATER MIXING
AGRICULTURE AND TERRESTRIAL ECOSYSTEMS
HUMAN SYSTEMS
ELECTRIC POWER INDUSTRY
COASTAL ECOSYSTEMS
POWER PLANTS
Stress

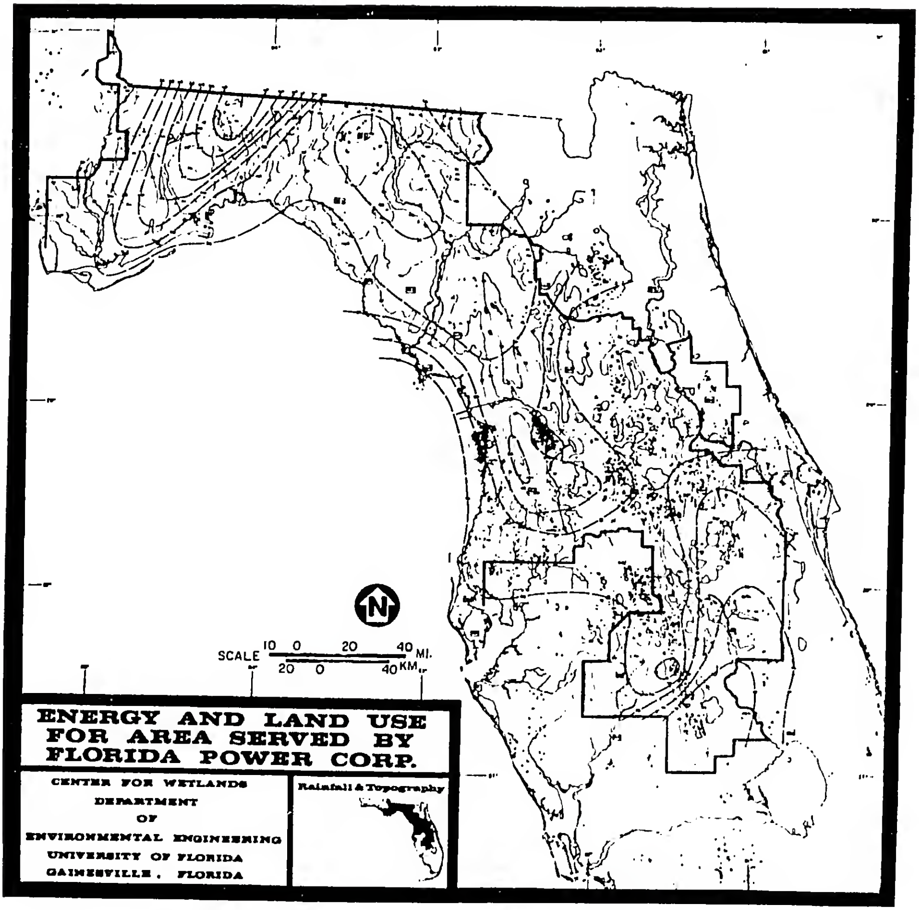
Figure 13. Reduced copy of vegetation and land use map of powershed regional study area for 1973. Map was drawn by interpreting shade, tone and texture patterns on N.A.S.A. - E.R.T.S. - 1, SATELLITE IMAGE MOSAIC, 1973 (1 inch = 8 miles) with questioned areas ground-truthed, and by referring to the SCS General Florida Vegetation Map developed by J.H. Davis (1967). Base map was developed from USGS map of Florida (1966). Interpretation was done with assistance of F. Ramsey, and map was drafted by L. Arrington. Note that "vegetable" crops includes corn and melons as well. Full sized maps are available from Center for Wetlands, University of Florida.



ENERGY AND LAND USE FOR AREA SERVED BY FLORIDA POWER CORP.

CENTER FOR WETLANDS
DEPARTMENT
OF
ENVIRONMENTAL ENGINEERING
UNIVERSITY OF FLORIDA
GAINESVILLE, FLORIDA

Figure 14. Map of rainfall and topography developed for calculating the potential energy of elevated water from rainfall on the landscape in powershed region. Rainfall data was obtained from NOAA (1971) and topographic data were taken from Raisz and Dunkle (1964).


N
SCALE
10 0 20 40 MI.
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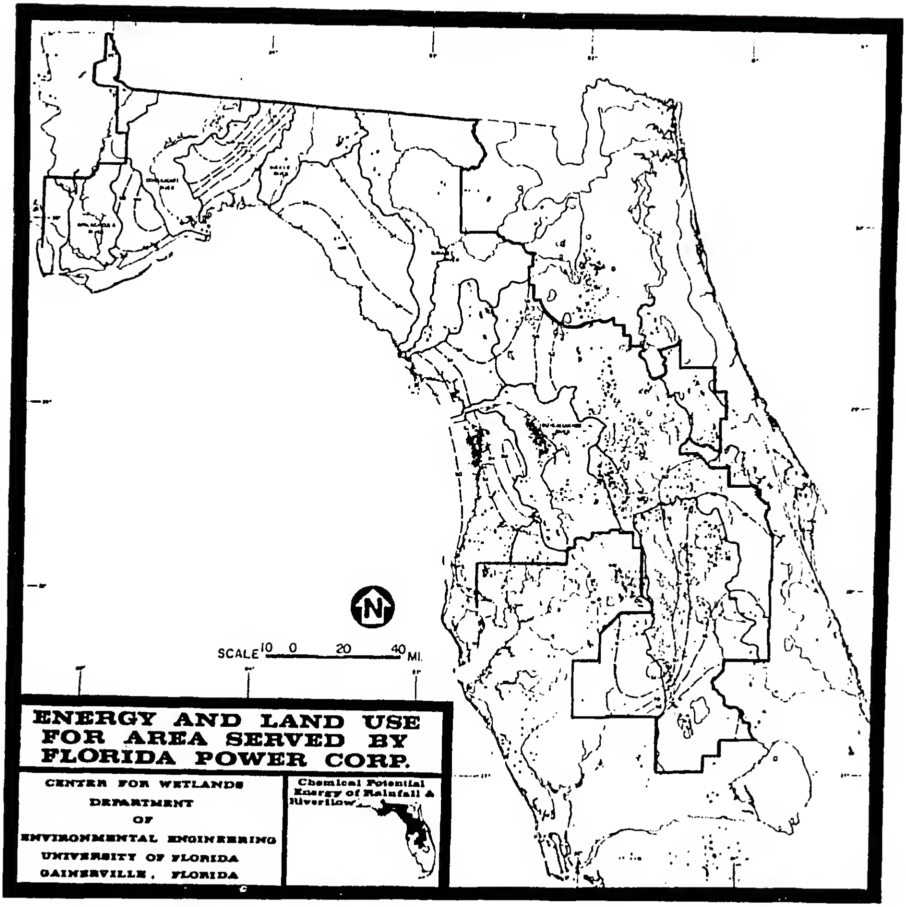
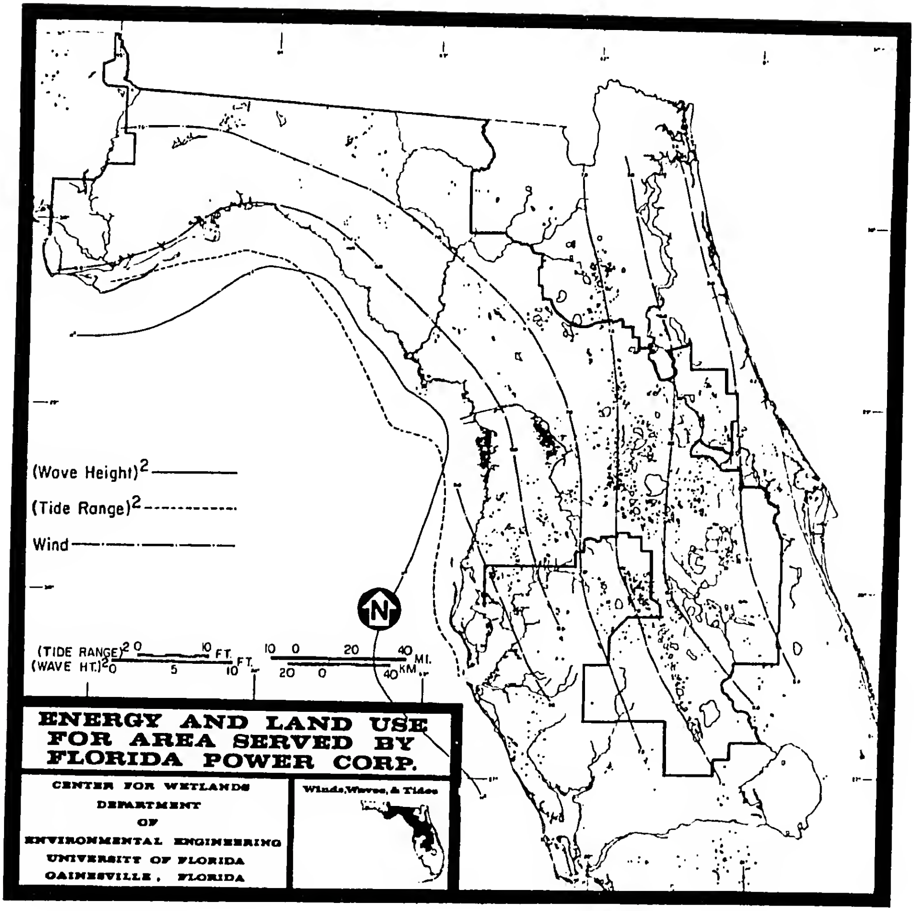
GAINESVILLE, FLORIDA
Rainfall & Topography

Figure 15. Map of rainfall and riverflow developed for calculating the chemical potential energy of freshwater relative to seawater in powershed region. River-flow data (McNulty et al., 1972) is used for watersheds with gauged streams, and rainfall and runoff estimates (G.G. Parker, 1974) are used for the remainder of the study area.



ENERGY AND LAND USE FOR AREA SERVED BY FLORIDA POWER CORP.

Figure 16. Map of mean wind speeds, tidal range and wave height in regional study area developed for calculating the energy inputs from these sources to the powershed regional system. Wind data are taken from NOAA (1955-71); tide data are from NOAA (1973); and wave data are from Walton (1973). The mean annual magnitudes of wave height and tidal range are represented as the normal distance from the main coastline to the appropriately marked line drawn offshore from the coast.


(Wave Height)2
(Tide Range)2
Wind
N
(TIDE RANGE)2 0 10 FT.
(WAVE HT.)2 0 5 10 FT.
10 0 20 40 MI.
20 0 40 KM.
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Winds, Waves, & Tides

classifications were also employed. The limit of this maps' resolution is about 1 km^2, so that areas less than a square kilometer were generally not detectable. The estimated total areas in each category are given in Table 6, corrected to correspond to legal surveys of county dimensions (BEBR, 1975).

The most prevalent ecosystems (see Odum and Brown, 1975 for detailed descriptions) in this region are pine flatwoods which are dispersed throughout, with large strands in the northwest part of the region. This ecosystem includes both relatively natural areas and managed pine plantations. Managed areas with extensive clear-cutting and only seedling stands were classified separately. Running longitudinally down the central highlands of the state is a wide band of managed land. In the southern and southeastern parts of the region, this land is primarily in pasture. However, Florida's prime citrus belt is located on a band which connects Gainesville and Lake Okeechobee. By far the dominant land use in the north central part of the powershed is for vegetable, corn and melon crops. The highland ridge along the Gulf Coast near Crystal River is characterized by extensive longleaf pine/turkey oak communities. Hardwood forest ecosystems are generally located in river floodplains and coastal swamps. Estimates of total regional productivity for the communities designated in Fig. 13 are given in Table 6. The highest rates of gross primary production were for freshwater marshes, pastures, and citrus crops, while the communities contributing most to the region's total gross productivity were pasture, vegetable (plus corn and melons) crops, pine flatwoods and citrus crops.

Energy input to the region through hydrostatic head of water

Table 6. Summary of ecosystem areas and productivities in powershed.

Ecosystem Type		Area,* m^2 (10^9)		Productivity Estimate (10^3) kcal/m^2-yr		Regional Productivity, (10^{12}) kcal/yr
No.	Name	Map measured	Survey corrected	Gross productivity	Source of estimate	
5	Industrial extraction	0.07	0.08	2.6	E.P. Odum (1971)	0.21
6	Urbanized systems	.86	.93	1.3	E.P. Odum (1971)	1.21
9	Pasture	9.56	10.29	45.3	Bayley and Burns (1974); Schroeder (1958)	466.14
10	Vegetable crops	8.10	8.72	28.5	Lemon et al. (1971) x (180/365) crop days	248.52
11	Citrus crops	3.38	3.64	38.2	Bayley et al. (1976a)	139.05
12	Pine seedling stands	0.11	0.12	4.0	Ovington (1961); Woodwell and Whittaker (1968)	0.48
14a	Pine flatwoods	13.44	14.66	11.9	"	174.45
14b	Sand pine	0.18	0.19	6.0	"	1.14
14c	Longleaf pine/ turkey oak	3.52	3.79	12.0	Whittaker and Woodwell (1969)	45.48
15a	Mixed hardwoods	0.49	0.52	16.6	Ovington (1962); Spurr and Barnes (1973)	8.63

Table 6. (Continued)

Ecosystem Type		Area,* m^2 (10^9)		Productivity Estimate (10^3) kcal/m^2-yr		Regional Productivity, (10^{12}) kcal/yr
No.	Name	Map measured	Survey corrected	Gross productivity	Source of estimate	
15b	Upland hardwoods	1.03	1.11	9.1	Ovington (1962)	10.10
15c	Hydric hardwoods	4.53	4.87	17.1	Mitsch (1975)	83.28
16	Lakes and Ponds	1.35	1.45	6.6	Nordlie (1975)	9.57
17	Cypress domes and strands	0.37	0.40	5.3	Cowles (1975); Carter et al. (1973)	2.12
18	Wet prairie	0.79	0.85	16.6	Carter et al. (1973)	14.11
20	Freshwater marshes	1.01	1.09	72.3	Bayley and Burns (1974); Westlake (1963)	78.81
22	Beaches and dunes	0.08	0.09	1.8	E.P. Odum (1971)	0.16
25	Saltmarsh and mangrove	0.72	0.77	27.7	Young (1974b); Golley et al. (1962); Lugo and Snedaker (1974)	21.33
9/17	Pasture/cypress	0.86	0.92	39.2	Prorated 65/35	36.06
14a/9	Flatwoods/pasture	0.19	0.20	27.9	Prorated 65/35	5.58

Table 6. (Continued)

Ecosystem Type		Area,* m^2 (10^9)		Productivity Estimate (10^3) kcal/m^2-yr		
No.	Name	Map measured	Survey corrected	Gross productivity	Source of estimate	Regional Productivity, (10^{12}) kcal/yr
14a/9/17	Flatwoods/ pasture/cypress	0.30	0.32	24.3	Prorated 50/30/20	7.78
17/14a	Cypress/flatwoods	0.09	0.10	7.6	Prorated 65/35	0.76
	Total					1354.97

---

* Areas measured from vegetation map, Fig. 13, and corrected (7% discrepancy) for the legal areas reported in Florida Statistical Abstracts (BEBR, 1975).

elevated on the landscape was calculated using rainfall and topographic data (from NOAA, 1971 and Raisz and Dunkle, 1964, respectively). Notice in Fig. 14 that the areas of maximum rainfall correspond to the more elevated regions, including panhandle area and the Gulf Coast ridge near Crystal River. Rainfall patterns, along with riverflow, are shown in Fig. 15, where these data were used to calculate the chemical potential energy (ΔG) of freshwater in the region (relative to seawater. The major watersheds for rivers whose flows are gauged are outlined on this map within the powershed region. Between these watershed boundaries are those areas whose rainfall flows to the sea via small, ungauged creeks or via other large rivers which are not gauged at the point where they leave the region. Notice in Fig. 15 that slightly more than one-third of the powershed region is included as watershed areas whose rivers are gauged as they leave the region.

A map of mean wind speeds, tidal range and wave height is given in Fig. 16 for the regional study area. Isopleths are drawn for wind speeds of 11.3, 12.9 and 14.5 km/hr (7.0, 8.0 and 9.0 mph). In general mean annual wind speeds are highest near the coast and lowest over the central ridge. Mean winds in excess of 14.5 km/hr (9.0 mph) occur in the St. Petersburg area on the Gulf side and on the Atlantic side near Orlando. The mean annual magnitudes of wave height and tidal range along the Gulf Coast are represented as the normal distance from the main coastline to the appropriately marked line drawn offshore from the coast. Tides are relatively constant along the coast, with reduced tides in embayed areas. Waves are greater where the Gulf shelf is narrower, with minimum wave energy occurring near the mouth of the Suwanee River and maximum values near St. Petersburg.

Summary of Natural Energy Inputs

Annual flows of "renewable" energies into the powershed region calculated from data presented in Figs. 13-16 are summarized in Table 7. The methodologic and mathematic details are given in footnotes which follow the table. The estimated caloric or heat values of these energies were converted to coal equivalent (CE) Calories (i.e., the number of Calories of coal energy needed to accomplish the same work), using energy quality ratios. Energy data are given in coal equivalents (CE) so that the diverse kinds of energies considered in the study can be compared on a common basis, viz. their ability to do work. These ratios, also given in Table 7, were estimated from energy and economic analysis of various industrial work processes. Notice that the total coal equivalent energy value from nature is barely 7% of the heat value for the same energy flows.

Almost two-thirds of natural energy inputs to the powershed region come from solar radiation used in photosynthesis. Of this only 2% is contributed from the coastal marine ecosystems apportioned to the region for this analysis. The chemical potential of freshwater entering the region either as rain or runoff comprises slightly more than 1% of the total natural energies. A lack of significant topography in the region results in relatively small (2.0% of total) contributions of potential energy of elevated water despite plentiful rainfall. While the heat equivalent of wind energy in the ragion is substantial, its relatively low quality indicates only small input to the total region (2.8%). The wave and tidal energies of the sea constitute some 12% of the total natural inputs to the region, even though mean wave height

Table 7. Summary of annual inputs of natural energy to power plant region.

Energy source	Foot-note	Energy flow in heat equivalents kcal x 10^{12}/yr	Energy quality factor[a]	Energy flow in coal equivalents kcal x 10^{12}/yr
Contributing Natural Energy Sources[b]				
Potential energy of elevated water	c	1.2	1.7	2.1
Chemical potential of freshwater	d	0.5	3.1	1.6
Kinetic energy of wind	e	28.5	0.1	2.9
Potential energy of waves	f	5.8	1.2	7.0
Potential energy of tides	g	3.0	1.5	4.5
Metabolic Energy Flows in Natural Systems				
Terrestrial productivity	h			
Agricultural systems		855.6	.05	42.8
Natural systems		499.4	.05	25.0
Marine productivity	i			
Estuarine systems		9.7	.05	0.5
Coastal plankton		22.5	.05	1.1
Total		1585.6		102.0

[a] Estimated from analysis of detailed data for pertinent work processes. See Table 5 and Odum et al. (1975) for derivations.

[b] Other contributing energy sources not considered here include the potential energy generated by thermal gradients over the region and potential energy associated with saturation deficit in atmospheric vapor pressure.

Table 7. (Continued)

[c]Potential energy of elevated water

Power Flow, $P_{RH} = \rho g \sum_{j} \sum_{i} Q_i h_j$ (26)

ρ = density of water, 1 g/cm^3
g = gravitational acceleration, 980 cm/sec^3
Q_i = total runoff and infiltrate between isohyetals, cm^3/yr (Raisz and Dunkle, 1964; NOAA, 1963-74)
h_j = elevation of water above sea between topo-lines, cm

$$Q_h = 172.18 \times 10^{16}\ ft \cdot \frac{cm^3}{yr} \quad (30.48\ \frac{cm}{ft})$$
$$= 52.5 \times 10^{18}\ cm \cdot \frac{cm^3}{yr}$$

$$P_{RH} = \rho g \sum \sum Q \cdot h = (980\ \frac{g \cdot cm}{cm^3 \cdot sec^2})(52.5 \times 10^{18}\ \frac{cm \cdot cm^3}{yr})$$
$$= 5.14 \times 10^{22}\ ergs/yr\ (2.38 \times 10^{-11}\ \frac{kcal}{erg})$$
$$= 1.22 \times 10^{12}\ kcal/yr$$

[d]Chemical potential energy

Power Flow, $P_{cp} = \Delta G(Q)M_s = nRT\ Ln\ \frac{C_1}{C_2}\ (Q)M_s$ (27)

n = 1 mole/35g (NaCl): R = gas constant = 1.99 cal/mole°K
T = annual mean water temperature = 20°C = 293°K
C_1 = rain concentration of dissolved solute = 1.2 ppm
C_2 = solute concentration of river water = 120 ppm
Q = total runoff = $48.5 \times 10^9\ m^3/yr$ (NOAA, 1963-74; G.G. Parker, 1974)
M_s = concentration of salt = 120 g/m^3

$$P_{cp} = (\frac{1\ mole}{35\ g})(1.99 \times 10^{-3}\ kcal/M\ K)(293\ K) Ln(\frac{1.2}{120})(48.5 \times 10^9\ m^3/yr) \cdot (120\ g/m^3)$$
$$= 0.45 \times 10^{12}\ kcal/yr$$

[e]Wind energy

Power Flow, $P_w = 1/2\ \rho V^2 A_s C_e (\frac{1}{d})$ (28)

ρ = density of air = $1.2 \times 10^{-3}\ g/cm^3$
A_s = surface area of region upon which wind does work = $5.52 \times 10^{14}\ cm^2$
V = mean wind speed at given ht. = 11.1 ft/sec = 338 cm/sec (NOAA, 1971)
C_e = eddy diffusion coefficient = $10^4\ cm^2/sec$ (Odum, 1974a)
d = height above ground of measured wind speed = 10^4 cm

Table 7. (Continued)

$$P_w = 1/2\ (1.2 \times 10^{-3}\ g/cm^3)(338.3\ \frac{cm}{sec})^2 (5.52 \times 10^{14}\ cm^2) \cdot$$
$$(10^4\ cm^2/sec)(\frac{1}{10^4\ cm})$$
$$= 3.79 \times 10^{16}\ ergs/sec\ (3.15 \times 10^7\ \frac{sec}{yr})(2.39 \times 10^{-11}\ kcal/erg)$$
$$= 28.53 \times 10^{12}\ kcal/yr$$

[f] Wave energy

Power Flow, $P_{wv} = 1/8\ \rho g^{3/2}\ H^{5/2}\ L$ (for shallow waves, $\frac{H}{L} < .05$) (29)

ρ = density of sea water = 1.025 g/cm^3
g = acceleration of gravity = 980 cm/sec^2
H = height of wave = 69.2 cm (Walton, 1973)
L = length of wave crest = 308 mi = 4.95×10^7 cm

$$P_{wv} = 1/8\ (1.025\ g/cm^3)(980\ cm/sec^2)^{3/2}\ (69.19\ cm)^{5/2}\ (4.95 \times 10^7\ cm)$$
$$= 7.74 \times 10^{15}\ ergs/sec\ (3.15 \times 10^7\ \frac{sec}{yr})(2.38 \times 10^{-11}\ \frac{kcal}{erg})$$
$$= 5.81 \times 10^{12}\ kcal/yr$$

[g] Tidal energy

Power Flow, $P_T = 1/2\ \rho g\ A_{ws} h^2 n_t$ (30)

ρ = density of sea water = 1.025 g/cm^3
g = acceleration of gravity = 980 cm/sec^2
h = height of tidal range = 2.3' = 70.10 cm (NOAA, 1973)
A_{ws} = area of water surface = (308 mi coast)(10 mi wide zone) = $(4.95 \times 10^7\ cm)(.145 \times 10^7\ cm) = 7.98 \times 10^{13}\ cm^2$
n_t = number of tides/yr = 705

$$P_T = 1/2\ (1.025\ gm/cm^3)(980\ cm/sec^2)(7.98 \times 10^{13}\ cm^2)(70.1\ cm)^2$$
$$= 1.77 \times 10^{20}\ \frac{g \cdot cm^2}{sec^2}\ (ergs)/cycle$$
$$= (1.77 \times 10^{20}\ ergs/cycle)(705\ cycles/yr)$$
$$= (1.25 \times 10^{23}\ ergs/yr)(2.38 \times 10^{-11}\ \frac{kcal}{erg})$$
$$= 2.97 \times 10^{12}\ kcal/yr$$

[h] Terrestrial productivity - see Table R2.

Table 7. (Continued)

[i] Marine productivity

Power Flow, $P_{MP} = M \times A$ (31)

M = gross primary productivity of ecosystem
 = 33.3 kcal/m^2/day for estuaries in region (Smith, 1976)
 = 8.6 kcal/m^2/day for coastal plankton to 9 miles offshore from (McKellar, 1975) plankton productivity measurements.

Estuaries:

$$P_{MP} = (308 \text{ mi})(1 \text{ mi})(2.59 \times 10^6 \frac{m^2}{mi^2})(33.3 \text{ kcal/m}^2\text{/day})(365 \text{ day/yr})$$
$$= 9.70 \times 10^{12} \text{ kcal/yr}$$

Coastal Plankton:

$$P_{MP} = (308 \text{ mi})(9 \text{ mi})(2.59 \times 10^6 \frac{m^2}{mi^2})(8.6 \text{ kcal/m}^2\text{/day})(365 \text{ day/yr})$$
$$= 22.54 \times 10^{12} \text{ kcal/yr}$$

and tidal range here are relatively small compared to other parts of Florida.

Analysis of Fuel and Economic Data

The quantities of various fuels used to generate electricity in the powershed region were calculated from data assembled in Table 8. The estimated per capita levels of consumption of fuels for uses other than electricity generation are shown in Table 9. Energy and economic data developed in this study are broken-down into major component flows for four economic subcategories in Fig. 17. The four categories of inputs and outputs generally correspond with Fig. 12 and are depicted separately in Fig. 17 as (a) fuels, (b) manufacture and sales, (c) government payments and (d) tourism and migration. Data given in Fig. 17 are also tabulated in Table 10 providing both economic and energy equivalents. In Fig. 17a eight kinds of fuels used in the powershed are shown as inputs to the electric power industry and into the remainder of the regional economy. Residual and crude oils made up 58% of the total fuels used in the power industry, and natural gas comprised nearly 14% of total power plant fuels, while the direct import of electricity accounted for about 23% of the fuel energy input to the powershed.

Approximately 44% of all fuels imported to the powershed region were used by electric utility industries. Within the remainder of the regional economy, gasoline was by far the most important fuel, comprising some 55% of the non-electric fuels and about 31% of the total fuels. Imports of residual and crude oils, middle distillate oils,

Table 8. Electric power generation and fossil fuel consumption by power plants in study region for 1973.[a]

Power plants	Generating capacity, MWE	Net electricity generation, MWH x 10^6/yr				Fuel consumption x 10^6/yr			
		Natural gas	Heavy oil	Light oil	Total	Nat. gas, 10^6 x ft^3	Hvy. oil, bbl	Lt. oil. bbl	Coal, tons
Fla. Power Corp.	2630	1.577	10.884	0.652	13.114	105.631	34.095	0.566	
Reedy Creek	5.5	0.033	0	0.021	0.054	0.334	0	0.038	
Kissimmee	20	0.059	0	0.030	0.089	0.597	0	0.057	
St. Cloud	19	0.047	0	0.010	0.058	0.518	0	0.020	
Sebring	24.5	0.036	0.018	0.007	0.061	0.509	0.046	0.014	
Starke	6.9	0.020	0	0.009	0.029	0.240	0	0.018	
Tallahassee	280	0.643	0.267	0.006	0.016	7.153	0.524	0.017	
Wauchula	7.6	0	0	0.004	0.004	0	0	0.007	
Orlando[b]	120	0.218	0.286	0.001	0.605	3.410	0.495	0.002	
Gainesville	225	---	---	---	---	---	---	---	
Gulf Power[c]	130	---	---	---	0.433	---	---	---	0.2243
Totals	3468.5	2.733	11.455	0.740	15.363				

[a] Data from FEDC, Florida Energy Data Center (1975) and Shrode et al. (1975).

[b] Orlando Plant = 120 MWE of Orlando Power Co.'s total 390 MWE.

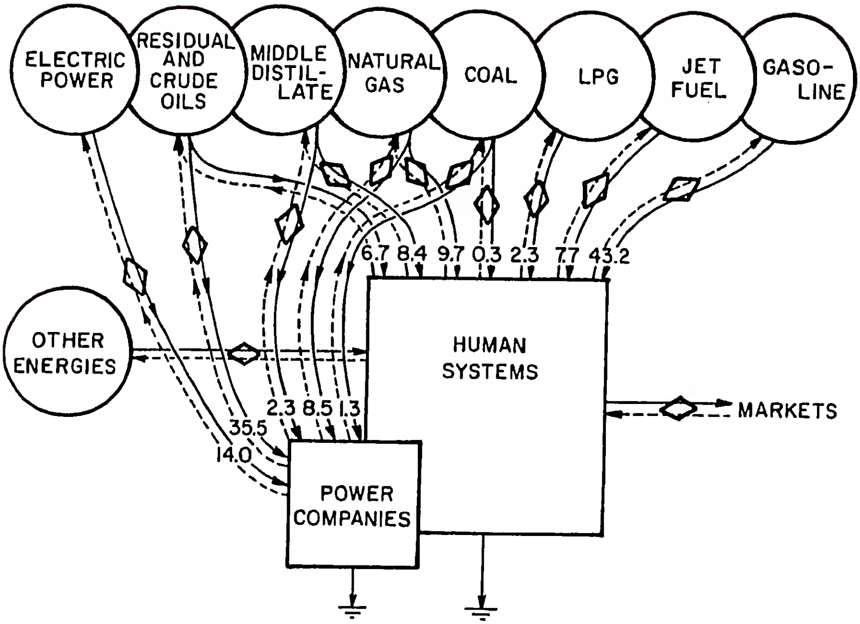
[c] Scholz Plant = 130 MWE of Gulf Power Corp.'s total 1300 MWE.

Table 9. Fuel consumption patterns for Florida, 1973.*

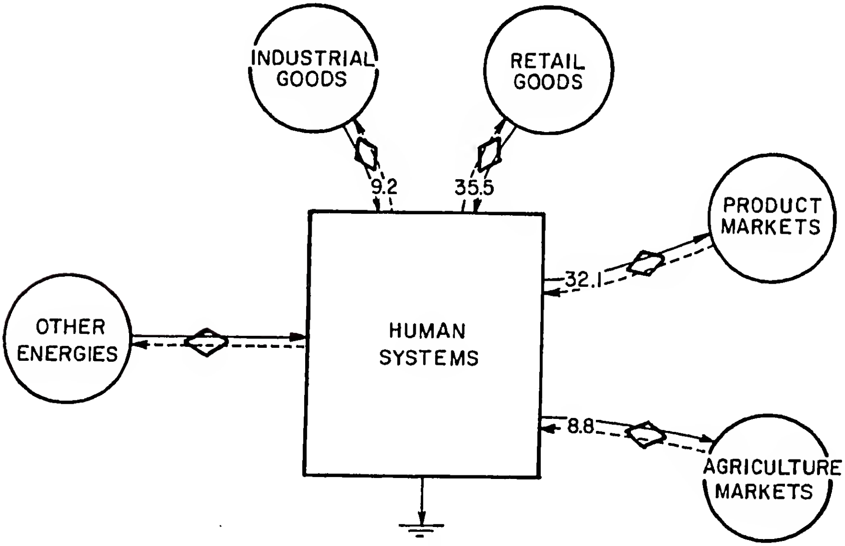
Fuel Type	BTU x 10^{12}/yr		Percent total for electric utilities	Per capita use of non-electric fuels 10^6 BTU/yr
	Non-electric consumption	Electric consumption		
Gasoline	539.4	0	0	68.76
Residual oil	94.0	426.0	82	11.98
Crude oil	4.1	10.4	72	0.52
Middle distillates	123.8	16.5	12	15.78
LPG	33.6	0	0	4.28
Jet fuel	113.4	0	0	14.46
Natural gas	143.5	176.0	55	18.29
Coal	3.9	150.2	97	0.50
Hydro	0	0.8	100	0
Nuclear	0	49.9	100	0
Total	1055.7	829.8		

* Data from FEDC, Florida Energy Data Center (1974b) and BEBR, Bureau of Economic and Business Research (1974).

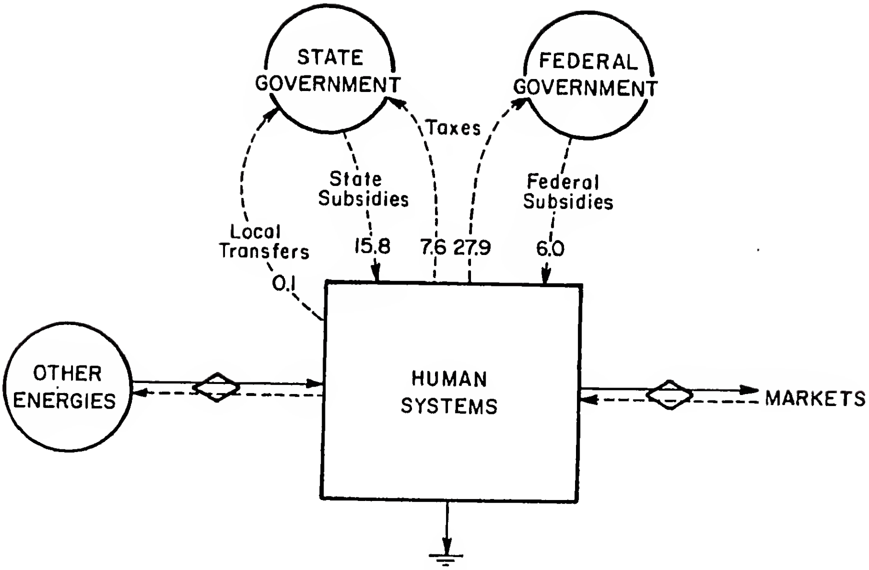
Figure 17. Unit model with details of energy budget for human systems depicted in Fig. 12 and listed in Table 10. Numbers on pathways represent energy flows in 10^{12} Kcal Coal Equivalents (CE)/year. The four economic subcategories given in the figure are (a) Fuels, (b) Manufacture and sales, (c) Government payments and (d) Tourism and migration.


ELECTRIC POWER
RESIDUAL AND CRUDE OILS
MIDDLE DISTIL-LATE
NATURAL GAS
COAL
LPG
JET FUEL
GASO-LINE
6.7
8.4
9.7
0.3
2.3
7.7
43.2
OTHER ENERGIES
HUMAN SYSTEMS
MARKETS
2.3
8.5
1.3
35.5
14.0
POWER COMPANIES

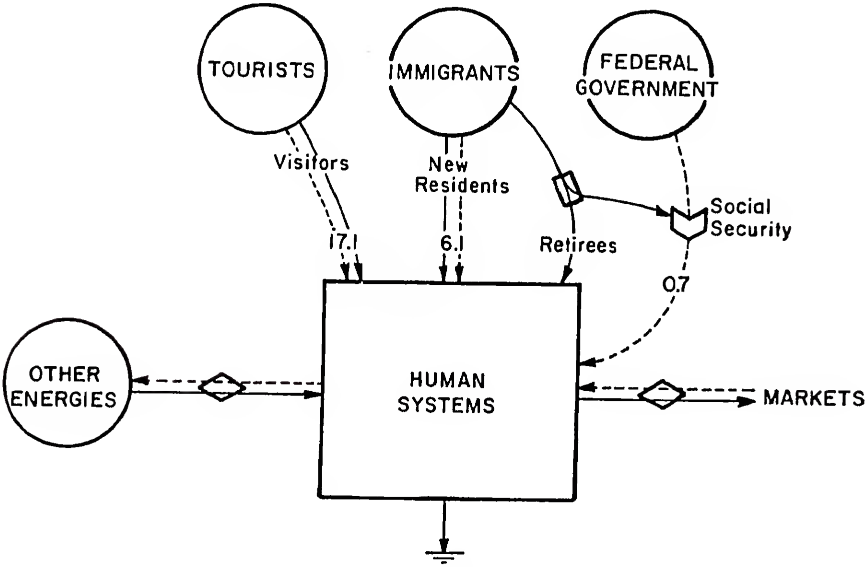
(a)


INDUSTRIAL GOODS
RETAIL GOODS
9.2
35.5
PRODUCT MARKETS
32.1
OTHER ENERGIES
HUMAN SYSTEMS
8.8
AGRICULTURE MARKETS

(b)


STATE GOVERNMENT
FEDERAL GOVERNMENT
Taxes
State Subsidies
Federal Subsidies
Local Transfers
15.8
7.6
27.9
6.0
0.1
OTHER ENERGIES
HUMAN SYSTEMS
MARKETS

(c)


TOURISTS
IMMIGRANTS
FEDERAL GOVERNMENT
Visitors
New Residents
Retirees
Social Security
17.1
6.1
0.7
OTHER ENERGIES
HUMAN SYSTEMS
MARKETS

(d)

Table 10. Summary of economic and energy flows into and out from the Anclote power plant region for 1973.

Name of flow	Foot-note	Economic flows, 1973 U.S. dollars x 10^6/yr (+in, -out)	Energy flows, Kcal CE x 10^{12}/yr (+in, -out)
Power Plant Fuels:			
Purchased Electricity	a	-106.6	+14.02
Residual Crude Oils	b	-106.4	+35.49
Middle Distillates	c	-6.9	+2.29
Natural Gas	d	-43.2	+8.47
Coal	e	-1.6	+1.34
Subtotal, Power Plant Fuels		-264.7	+61.61
Other Imported Fuels:			
Residual and Crude Oils	f	-20.0	+6.65
Middle Distillate	g	-25.2	+8.39
Natural Gas	h	-49.6	+9.73
Coal	i	-0.3	+0.27
LPG	j	-6.8	+2.28
Jet Fuel	k	-84.6	+7.69
Gasoline	l	-474.9	+43.17
Subtotal, All Fuels		-926.1	+139.79
Manufacture and Sales:			
Industrial Materials	m	-590.65	+11.81
Retail Goods	n	-1773.37	+35.47
Exported Goods	o	+1606.11	-32.12
Exported Foods	p	+439.68	-8.79
Government Payments:			
State Taxes	q	-381.03	-7.62

Table 10. (Continued)

Name of flow	Footnote	Economic flows, 1975 U.S. dollars x 10^6/yr (+in, -out)	Energy flows, Kcal CE x 10^{12}/yr (+in, -out)
Federal Taxes	r	-1394.68	-27.89
State Subsidy	s	+791.25	+15.83
Federal Subsidy	t	+299.85	+6.00
Local Transfers	u	-4.65	-0.09
Tourism and Migration:			
Highway Tourism	v	+681.31	-13.63
Common Carrier Tourism	w	+173.50	-3.47
Immigration	x	+305.67	+6.11
Immigrant Retiress	y	+34.96	+0.70
Total Trade		9402.81	309.32
Total Ecnomic Input		+4332.33	-93.61
Total Economic Output		-5070.48	+215.71
Difference		-738.15	+122.10

[a] Purchased electric power (1973-74):
Total electric demand in region (Pozzo, 1975) = 19.889 x 10^6 MWH
Total electric generation in region (Table 8) = 15.363 x 10^6 MWH
Total import of electric power = 4.526 x 10^6 MWH
= 14.02 x 10^{12} Kcal CE/yr
Price of electricity (Zucchetto, 1975a) = \$0.76 x 10^{-5}/Kcal CE
Dollar value of total electr. import = (14.02 x 10^{12} Kcal/yr)·
(\$.76 x 10^{-5}/Kcal)
= \$106.6 x 10^6/yr

[b] Residual and crude oils for electricity:
Electricity generated by Resid. & Crude = 11.455 x 10^{12} $\frac{\text{w hr}}{\text{yr}}$
(see Table 8)

Table 10. (Continued)

Energy used to generate electr. = $(11.455 \times 10^{12} \frac{\text{w hr}}{\text{yr}})(.8605 \frac{\text{Kcal}}{\text{w hr}})\cdot$
$(3.6 \frac{\text{Kcal coal}}{\text{Kcal elec.}})$
$= 35.49 \times 10^{12}$ Kcal CE/yr

Price of Resid. and Crude (Zucchetto, 1975a) = $\$0.3 \times 10^{-5}$/Kcal CE
Dollar value of Resid. and Crude = $(35.49 \times 10^{12}$ Kcal/yr$)\cdot$
$(\$0.3 \times 10^{-5}$/Kcal$)$
$= \$106.46 \times 10^{6}$/yr

[c]Middle distillates for electricity:

Electricity generated by Midl Distill. = $0.740 \times 10^{12} \frac{\text{watt-hr}}{\text{yr}}$
(see Table 8)

Energy used to generate electr. = $(.740 \times 10^{12} \frac{\text{w hr}}{\text{yr}})(.8605 \frac{\text{Kcal}}{\text{w hr}})\cdot$
$(3.6 \frac{\text{Kcal coal}}{\text{Kcal elec.}})$
$= 2.292 \times 10^{12}$ Kcal CE/yr

Price of Mid. Distill. (Zucchetto, 1975a) = $\$0.3 \times 10^{-5}$/Kcal CE
Dollar value of Mid. Distill. = $(2.292 \times 10^{12}$ Kcal/yr$)(\$0.3 \times 10^{-5}$/Kcal$)$
$= \$6.89 \times 10^{6}$/yr

[d]Natural gas for electricity:

Electricity generated by Nat. Gas = $2.733 \times 10^{12} \frac{\text{watt-hr}}{\text{yr}}$
(see Table 8)

Energy used to generate electr. = $(2.733 \times 10^{12} \frac{\text{w hr}}{\text{yr}})(.8605 \frac{\text{Kcal}}{\text{w hr}})\cdot$
$(3.6 \frac{\text{Kcal coal}}{\text{Kcal elec.}})$
$= 8.466 \times 10^{12}$ Kcal CE/yr

Price of Nat. Gas (Zucchetto, 1975a) = $\$0.51 \times 10^{-5}$/Kcal CE
Dollar value of Nat. Gas = $(8.466 \times 10^{12}$ Kcal/yr$)(\$0.51 \times 10^{-5}$/Kcal$)$
$= \$43.18 \times 10^{6}$/yr

[e]Coal for electricity:

Electricity generated by coal = $0.433 \times 10^{12} \frac{\text{watt-hr}}{\text{yr}}$
(see Table 8)

Energy used to generate electr. = $(0.433 \times 10^{12} \frac{\text{w hr}}{\text{yr}})(.8605 \frac{\text{Kcal}}{\text{w hr}})\cdot$
$(3.6 \frac{\text{Kcal coal}}{\text{Kcal elec.}})$
$= 1.34 \times 10^{12}$ Kcal CE/yr

Price of coal (Ballentine, 1976; FEDC, 1975) = $\$0.12 \times 10^{-5}$/Kcal CE

Table 10. (Continued)

Dollar value of coal = $(1.34 \times 10^{12}$ Kcal/yr$)(\$.12 \times 10^{-5}$/Kcal$)$
= $\$1.61 \times 10^{6}$/yr

[f] Residual and crude oil for non-electric use:
Per-capita non-electric consumption = 12.50×10^{6} BTU/cap·yr
(see Table 9)

Energy use = $(12.5 \times 10^{6}$ BTU/cap·yr$)(.252 \frac{\text{Kcal}}{\text{BTU}})(2.1102 \times 10^{6}$ cap$)$
= 6.65×10^{12} Kcal/yr
= $(6.65 \times 10^{12})(.3 \times 10^{-5}) = \$19.95 \times 10^{6}$/yr
(see note b)

[g] Middle distillates for non-electric use:
Per-capita non-electric consumption = 15.78×10^{6} BTU/cap·yr
(see Table 9)

Energy use = $(15.78 \times 10^{6}$ BTU/cap·yr$)(.252 \frac{\text{Kcal}}{\text{BTU}})(2.1102 \times 10^{6}$ cap$)$
= 8.39×10^{12} Kcal CE/yr
= $(8.39 \times 10^{12}$ Kcal/yr$)(\$0.3 \times 10^{-5}$/Kcal$)$
= $\$25.2 \times 10^{6}$/yr
(see note c)

[h] Natural gas for non-electric use:
Per-capita non-electric consumption = 18.29×10^{6} BTU/cap·yr
(see Table 9)

Energy use = $(18.29 \times 10^{6}$ BTU/cap·yr$)(.252 \frac{\text{Kcal}}{\text{BTU}})(2.1102 \times 10^{6}$ cap$)$
= 9.73×10^{12} Kcal CE/yr
= $(9.73 \times 10^{12}$ Kcal/yr$)(\$0.51 \times 10^{-5}$/Kcal$)$
= $\$49.60 \times 10^{6}$/yr
(see note d)

[i] Coal for non-electric use:
Per-capita non-electric consumption = 0.50×10^{6} BTU/cap·yr
(see Table 9)

Energy use = $(0.50 \times 10^{6}$ BTU/cap·yr$)(.252 \frac{\text{Kcal}}{\text{BTU}})(2.1102 \times 10^{6}$ cap$)$
= 0.27×10^{12} Kcal CE/yr
= $(0.27 \times 10^{12}$ Kcal/yr$)(\$0.12 \times 10^{-5}$/Kcal$)$
= $\$0.32 \times 10^{6}$/yr
(see note e)

Table 10. (Continued)

[j]LPG:

Per-capita consumption = 4.28×10^6 BTU/cap·yr

(see Table 9)

Energy use = $(4.28 \times 10^6 \text{ BTU/cap·yr})(.252 \frac{\text{Kcal}}{\text{BTU}})(2.1102 \times 10^6 \text{ cap})$

$= 2.28 \times 10^{12}$ Kcal CE/yr

$= (2.28 \times 10^{12} \text{ Kcal/yr})(\$.3 \times 10^{-5}\text{/Kcal})$

$= \$6.83 \times 10^6\text{/yr}$

(Zucchetto, 1975a)

[k]Jet fuel:

Per-capita consumption = 14.46×10^6 BTU/cap·yr

(see Table 9)

Energy use = $(14.46 \times 10^6 \text{ BTU/cap·yr})(.252 \frac{\text{Kcal}}{\text{BTU}})(2.1102 \times 10^6 \text{ cap})$

$= 7.69 \times 10^{12}$ Kcal CE/yr

$= (7.69 \times 10^{12} \text{ Kcal/yr})(\$1.10 \times 10^{-5}\text{/Kcal})$

$= \$84.58 \times 10^6\text{/yr}$

(Zucchetto, 1975a)

[l]Gasoline:
Total consumption in 1973 (FSCC, 1974) = 1.1991×10^9 gal/yr
Energy per gallon (Zucchetto, 1975a) = 3.6×10^4 Kcal/gal
Energy use = $(1.1991 \times 10^9 \text{ gal/yr})(3.6 \times 10^4 \text{ Kcal/gal})$
$= 43.17 \times 10^{12}$ Kcal/yr
Price of gasoline = $\$1.10 \times 10^{-5}$/Kcal (Zucchetto, 1975a)
Dollar value = $(43.17 \times 10^{12} \text{ Kcal/yr})(\$1.1 \times 10^{-5}\text{/Kcal})$
$= \$474.85 \times 10^6\text{/yr}$

[m]Industrial materials:
Cost of materials for manufacturers in region (BEBR, 1973) = $\$1205.4 \times 10^6$
Portion of materials imported to region (see Table 11) = 0.38
Total import of manuf. materials = $(\$1205.4 \times 10^6)(.38)$
$= \$458.05 \times 10^6\text{/yr}$
Energy equivalent, assuming diversity of matls. = 20,000 Kcal/\$
(Kylstra, 1974)
Energy value = $(\$458.05 \times 10^6)(20{,}000 \text{ Kcal/\$}) = 9.16 \times 10^{12}$ Kcal CE/yr

[n]Retail goods:
Total retail sales in region (BEBR, 1973) = $\$2497.7 \times 10^6$
Portion of retail goods imported from outside region (see Table 12) = 0.71
Total import of retail goods = $(\$2497.7 \times 10^6)(.71) = \$1773.37 \times 10^6\text{/yr}$
Energy equivalent (Kylstra, 1974) = 20,00 Kcal/\$
Total energy value = $(\$1723.41 \times 10^6)(20{,}000 \text{ Kcal/\$})$
$= 35.47 \times 10^{12}$ Kcal CE/yr

Table 10. (Continued)

[o] Exported goods:
Total value of shipment of goods manuf. in region (BEBR, 1973)
= $\$2113.3 \times 10^6$/yr
Portion of region's manuf. goods exported from region (see Table 11)
= 0.76
Total of region's manuf. goods = ($\$2113.3 \times 10^6$/yr(.76)
= $\$1606.11 \times 10^6$/yr
Energy equivalent (Kylstra, 1974) = 20,000 Kcal/$
Total energy value = ($\$1606.11 \times 10^6$/yr)(20,000 Kcal/$)
= 32.12×10^{12} Kcal CE/yr

[p] Exported foods:
Market value of agricultural prod. for 1969 (FDACS, 1972) = $\$449.2 \times 10^6$
in 1973 dollars (BEBR, 1974) = $\$449.2 \times 10^6$)(1.473)
= $\$661.7 \times 10^6$
Dockside value of commercial fish for 1972 (DMR, 1973) = $\$54.71 \times 10^6$
in 1973 dollars (BEBR, 1974) = $\$54.71 \times 10^6$)(1.300) = $\$71.11 \times 10^6$
Total value of foods = $\$732.8 \times 10^6$/yr
Assume 60% is exported from region
Total export value of foods = $\$439.68 \times 10^6$/yr
Energy equivalent (Kylstra, 1974) = 20,000 Kcal/$
Total energy value of exported food = ($\$439.68 \times 10^6$/yr)(20,000 Kcal/$)
= 8.79×10^{12} Kcal CE/yr

[q] State taxes paid:
Total taxes paid to state by individ. and corporations in region for FY 73 (Dickinson, 1973) = $\$381.03 \times 10^6$/yr
Energy equivalent (Kylstra, 1974) = 20,000 Kcal/$
Energy value of state taxes = ($\$381.03 \times 10^6$)(20,000 Kcal/$)
= 7.62×10^{12} Kcal CE/yr

[r] Federal taxes paid:
Fed. IRS collection in Florida (BEBR, 1974) = $\$5,184.7 \times 10^6$
Portion of Fla. pop. in region = .269
Estimated IRS collect. in region = ($\$5184.7 \times 10^6$)(.260)
= $\$1394.68 \times 10^6$/yr
Energy equivalent (Kylstra, 1974) = 20,000 Kcal/$
Energy value of IRS collection = ($\$1394.68 \times 10^6$/yr)(20,000 Kcal/$)
= 27.89×10^{12} Kcal CE/yr

[s] State subsidy to region:
Per-capita state expenditure (BEBR, 1974) = $375/indiv.
Population in region (BEBR, 1974) = 2.110×10^6 indiv.
Total subsidy from state = ($375/indiv.)($2.110 \times 10^6$ indiv.)
= $\$791.25 \times 10^6$/yr
Energy equivalent (Kylstra, 1974) = 20,000 Kcal/$
Energy value of state subsity = ($\$791.25 \times 10^6$)(20,000)
= 15.83×10^{12} Kcal CE/yr

Table 10. (Continued)

[t] Federal subsidy to region:
Total Fed. expenditures in Florida, FY 73 (BEBR, 1974) = $\$1,114.69 \times 10^6$
Portion of Fla. population in region = 0.269
Estimated Fed. expendit. in region = $(\$1,114.69 \times 10^6)(.269)$
$= \$299.85 \times 10^6$/yr
Energy equivalent (Kylstra, 1974) = 20,000 Kcal/\$
Energy value of Fed. expenditures = $(\$299.85 \times 10^6)$(20,000 Kcal/\$)
$= 6.00 \times 10^{12}$ Kcal CE/yr

[u] Transfer payments from local govts. to state:
Total local payments to state (Dickinson, 1973) = $\$17.3 \times 10^6$/yr
Portion of state in region = 0.269
Estimated local govt. payments = $(\$17.3 \times 10^6/\text{yr})(.269)$
$= \$4.65 \times 10^6$/yr
Energy equivalent (Kylstra, 1974) = 20,000 Kcal/\$
Energy value of local govt. payments = $(\$4.65 \times 10^6/\text{yr})$(20,000 Kcal/\$)
$= 0.09 \times 10^{12}$ Kcal CE/yr

[v] Highway tourism:
Total highway tourists registering at "welcome station" in region (Div. Tourism, 1972) = 635.31×10^3
Assume 33% of highway tourists stop to regist. (Div. Tourism, 1972)
Assume mean tourist group size = 3.2 persons "
Assume mean expenditure by tourist = \$89.91/trip·person "
Total expenditure by highway tourists =
$(635.31 \times 10^3$ stops)(3.0 groups/stop)(3.2 person/group)(\$89.91/person)
$= \$548.36 \times 10^6$/yr (Div. Trouism, 1972)
Total "touring" tourists registering in Florida = 396.39×10^3
Percent total state "non-touring" trouist registered in region = 38.86
Assume "touring" tourists spend 38.86% of their trip costs within region (Div. Tourism, 1972)
Total expendit. by touring tourists = $396.39 \times 10^3(3)(3.2)(\$89.91)(.3886)$
$= \$132.95 \times 10^6$/yr
Total highway tourist expenditures = $\$681.31 \times 10^6$/yr
Energy equivalent (Kylstra, 1974) = 20,000 Kcal/\$
Energy value of highway tourism = $(\$681.31 \times 10^6)$(20,000 Kcal/\$)
$= 13.63 \times 10^{12}$ Kcal CE/yr

[w] Common carrier tourism:
Total common carrier passengers (Div. Tourism, 1972) = 9.932×10^6/yr
Assume 50% of these are tourists
Assume comm. carr. tourists vacation as do highway tourists, i.e., 38.86% in region
Assume mean expenditure is \$89.91/person·trip
Total expenditure by comm. carr. passengers
$= (9.932 \times 10^6/\text{yr})(.50)(.3886)(\$89.91/\text{person}) = \$173.50 \times 10^6$/yr
Energy equivalent (Kylstra, 1974) = 20,000 Kcal/\$
Energy value of comm. carr. tourism = 3.47×10^{12} Kcal CE/yr

Table 10. (Continued)

[x] Immigration:

Total net immigration to region for 39 mos. (BEBR, 1974) = 336.19×10^3

Annual immigration to region = 336.19×10^3 (12/39) = 103.44×10^3/yr

Mean bank deposits in U.S. = \$2955/person (BEBR, 1974)

Total capital influx with migrants = (103.44×10^3 person/yr)·(\$2955/person)
= \$$305.67 \times 10^6$/yr

Equivalent energy (Kylstra, 1974) = 20,000 Kcal/\$

Energy value of immigrant capital = (\$$305.67 \times 10^6$)(20,000 Kcal/\$)
= 6.11×10^{12} Kcal CE/yr

[y] Immigrating retirees:

Total increase in no. Fla. retirees, 1970-73 (BEBR, 1974)
= 193,067 persons

Annual increase in no. retirees = 193,067/3 = 64,356

Assume new retirees settle in proportion to existing population patterns, i.e., 26.9% in region.

Mean social security benefits for retirees = \$2019.24/yr

Total incr. soc. sec. benefits for new retirees in region
= (64,356 persons/yr)(.269)(\$2019.24/yr) = \$$34.96 \times 10^6$/yr

Energy equivalent (Kylstra, 1974) = 20,000 Kcal/\$

Energy value of new soc. sec. = (\$$34.96 \times 10^6$/yr)(20,000 Kcal/\$)
= 0.70×10^{12} Kcal CE/yr

natural gas, and jet fuel were very similar, each representing about 10% of the non-electric inputs of energy to the region. Coal was relatively unimportant as a fuel for the powershed economy as a whole, making up less than 2% of the total.

The import of goods to, and the export of products from, the powershed region are summarized in Fig. 17b, where industrial and retail goods are separated, as are agricultural and industrial products. As indicated in the footnotes to Table 10, data for import and export of goods from Florida were not directly available. It was necessary to calculate these material and money flows from data on sales and manufacturing in the region, applying an approximate import and/or export coefficient (indicating fraction of total sales going outside region and fraction of purchased goods originating outside region) for each item. Data for manufacture of goods from 20 different standard industrial classifications (SIC) were analyzed and coefficients were estimated to indicate the portion imported or exported for each category of goods. These data are given in Table 11. A similar analysis was done to estimate import of retail goods for nine categories of retailing, and this information is given in Table 12. Retail goods accounted for about 79% of the total imported value, while industrial products comprised over 78% of the total exports.

The exchange of dollars between governments is indicated in Fig. 17c, with state and federal subsidies entering the county and city governments in the powershed through various programs and projects, and local monies being returned to Tallahassee and Washington via commercial and personal taxes. Federal taxes represented the largest output of money to the government (78%), and state subsidies were the larger mode

Table 11. Estimated portions of goods annually manufactured in Florida which are exported from the state and raw materials for manufacturing which are imported from outside the state.

Kind of Business	Materials for manufacture, $ x 10^6			Manufactured products, $ x 10^6		
	Cost of[a] materials	Percent[b] imported	Total matl. import	Value[a] shipments	Percent[b] exported	Total export
Food	2.11	30	.63	3.06	80	2.45
Tobacco	.05	80	.04	.10	90	0.09
Textiles	.06	50	.03	.11	90	.10
Clothing	.24	70	.17	.39	80	.31
Lumber	.36	20	.07	.61	90	.55
Furniture	.11	20	.02	.23	80	.19
Paper	.45	30	.15	.81	70	.57
Printing	.20	30	.06	.68	30	.20
Chemicals	.58	70	.41	1.08	70	.71
Petroleum	.04	100	.04	.07	90	.06
Rubber	.09	100	.09	.21	90	.19
Leather	.02	50	.01	.05	90	.57
Stone, Clay	.35	30	.10	.71	70	.50

Table 11. (Continued)

Kind of Business	Materials for manufacture, $ x 10^6			Manufactured products, $ x 10^6		
	Cost of[a] materials	Percent[b] imported	Total matl. import	Value[a] shipments	Percent[b] exported	Total export
Primary Metals	.09	100	.09	.15	90	.15
Fabricated Metals	.51	90	.46	.93	90	.85
Machines	.25	60	.15	.53	80	.42
Electronic	.31	60	.19	.85	80	.68
Transp. Eqp.	.27	90	.24	.66	70	.46
Instruments	.05	80	.04	.14	70	.10
Misc.	.06	80	.05	.13	70	.09
Totals	6.19		3.04	11.50		8.72

Portion manufacturing materials imported = $\frac{3.04}{6.19}$ = 0.49

Portion manufactured goods export from region = $\frac{8.72}{11.50}$ = 0.76

[a] Data from BEBR, Bureau of Economic and Business Research (1974).

[b] Estimates based on examination of phone books, my own intuition, and discussion with Dr. Jesse Boyles, Accounting Department, University of Florida, Gainesville.

Table 12. Estimated portions of annual retail sales of various goods originating from within Florida.

Kind of Business	Retail[a] sales $\$ \times 10^9$	Percent[b] within state	Total in-state sources $\$ \times 10^6$
Building materials	1.06	80	.85
Department stores	2.91	25	.73
Food stores	4.04	50	2.02
Automobiles	4.34	5	0.22
Gasoline	1.38	0	0
Clothing stores	.98	25	.25
Furniture	1.05	50	.53
Restaurants & bars	1.79	25	0.45
Misc. retail stores	1.54	30	0.46
Totals	19.09		5.51

Estimated portion of retail sale of goods originating from within state $= \frac{5.51}{19.09} = 0.29$

---

[a] Data from BEBR, Bureau of Economic and Business Research (1974).

[b] Estimates based on examination of phone books, my own intuition and discussion with Dr. Jesse Boyles, Accounting Department University of Florida, Gainesville.

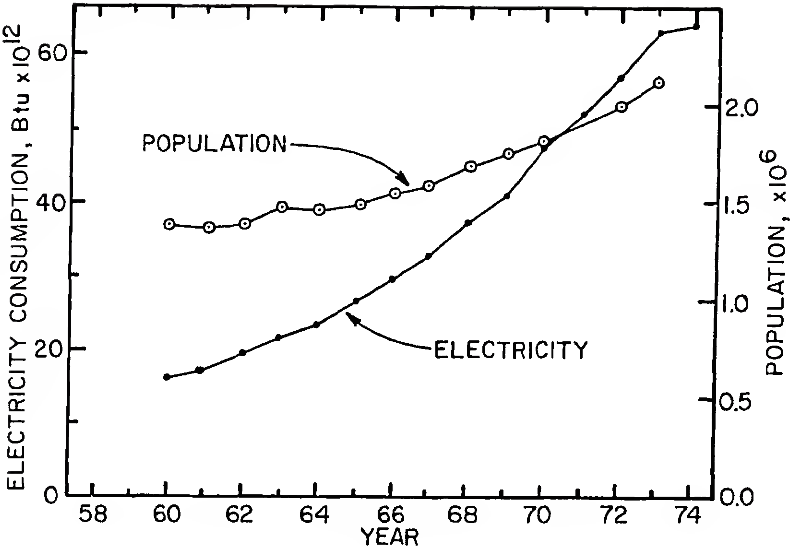
for returning some of the tax money (72%). In all, there was a substantial deficit to the powershed in the exchange of government money, where 62% more dollars left the region than were returned. The economic influx associated with tourism and immigration to the region is summarized in Fig. 17d. Tourism accounted for about 20% of the dollar input to the region. It was assumed that money flows into the region with new residents by means of their bank accounts, and this input was about 7% of the total monetary influx. Another small input which was considered was the social security payments to retirees moving to the region.

Economic and Energy History

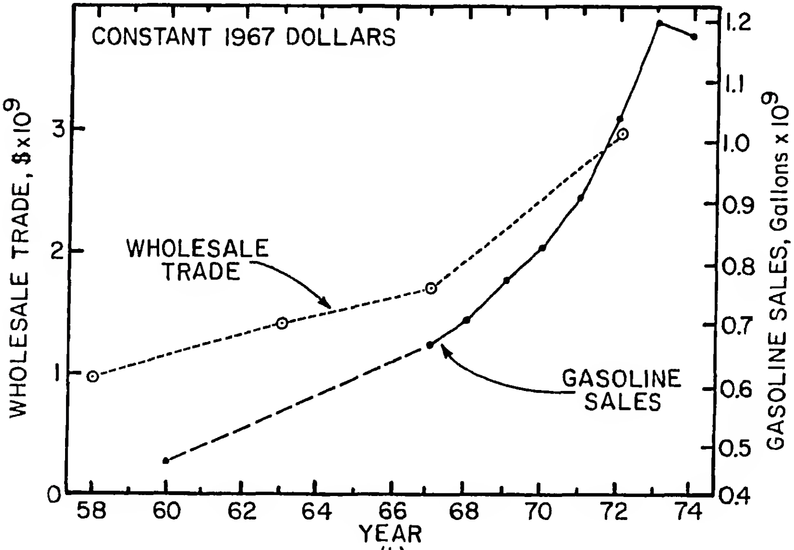
Selected economic and energy data for the Crystal River powershed over the past 10-15 yrs are presented in Fig. 18. These data indicate the region's growth trends and its dependence on natural and fossil-fuel-based energy resources. Each data point represents a tally of individual statistics for the 32 counties in the powershed region. Three types of measurements are given in this figure: parameters in Fig. 18a-c are indices of fossil-fuel-dependent sectors in the regional economy; parameters in Figs. 18d-e are measures of agricultural and fisheries industries which are primarily dependent on the renewable energies of nature; and Fig. 18f gives two of the principal energy inputs from nature, solar radiation and rainfall.

Referring to Fig. 18a it can be seen that population has been growing at a rate of about 3% per year, although the early 1960's showed little increase. Industry and commerce (as indicated by wholesale trade,

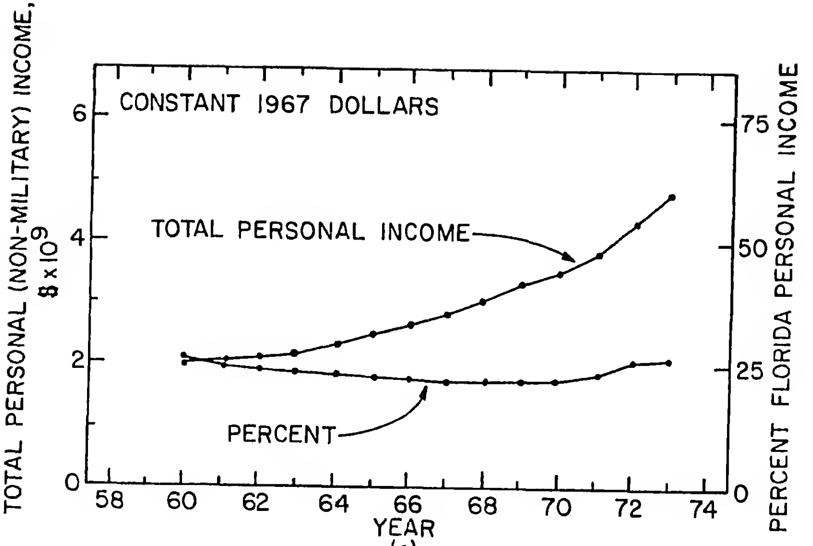
Figure 18. Annual trends in economic (constant 1967 dollars) and energy parameters for Crystal River power plant region from 1958-1974. (a) Regional population and electricity consumption. Population data from BEBR (1967-1975). Electricity consumption data from Pozzo (1975) for 1973-1974 and Schrode et al. (1975) for 1960-72. (b) Wholesale trade and gasoline sales. Data from BEBR (1967-75). (c) Total personal income (excluding agriculture) in region and percent of Florida total personal income. Data from BEBR (1967-75). (d) Personal agricultural income in region and percent of Florida personal agricultural income. Data from BEBR (1967-75). (e) Commercial fish landings for region in terms of quantity and dockside value. Data from DMR (1963-73). (f) Mean daily solar radiation and annual rainfall for region. Solar radiation data from NOAA (1955-71) and rainfall data from NOAA (1963-74).


ELECTRICITY CONSUMPTION, Btu x 10^{12}
0
20
40
60
POPULATION
ELECTRICITY
POPULATION, x10^6
0.0
0.5
1.0
1.5
2.0
58
60
62
64
66
68
70
72
74
YEAR

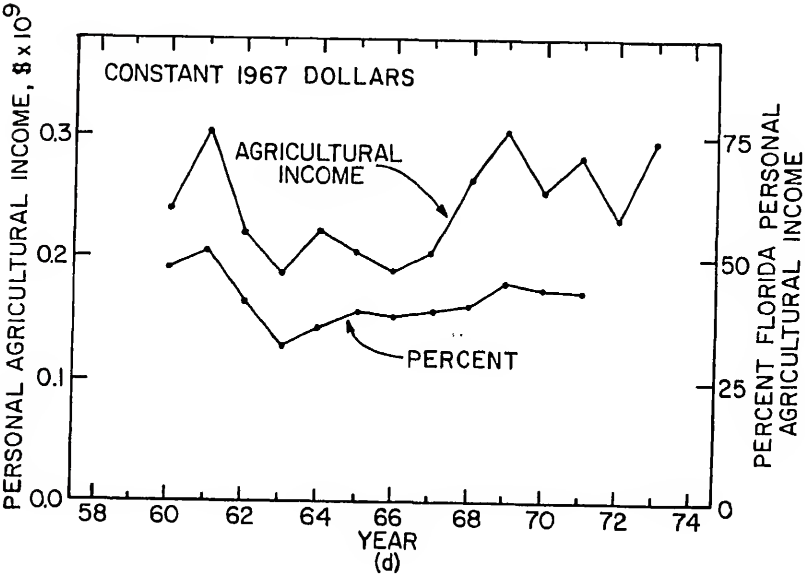
(a)


CONSTANT 1967 DOLLARS
WHOLESALE TRADE, $ x 10^9
0
1
2
3
WHOLESALE TRADE
GASOLINE SALES
GASOLINE SALES, Gallons x 10^9
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
58
60
62
64
66
68
70
72
74
YEAR

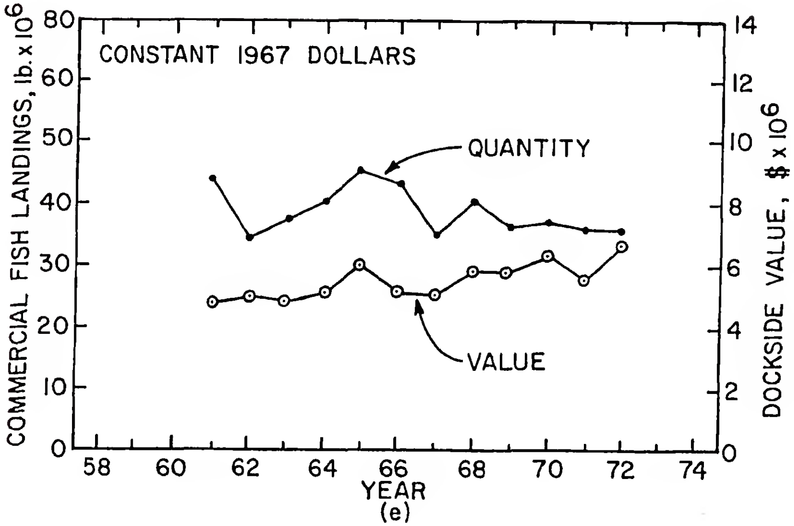
(b)


CONSTANT 1967 DOLLARS
TOTAL PERSONAL INCOME
PERCENT
TOTAL PERSONAL (NON-MILITARY) INCOME, $\$ \times 10^9$
0
2
4
6
PERCENT FLORIDA PERSONAL INCOME
0
25
50
75
58
60
62
64
66
68
70
72
74
YEAR

(c)


CONSTANT 1967 DOLLARS
AGRICULTURAL INCOME
PERCENT
PERSONAL AGRICULTURAL INCOME, $\$ \times 10^9$
0.0
0.1
0.2
0.3
PERCENT FLORIDA PERSONAL AGRICULTURAL INCOME
0
25
50
75
58
60
62
64
66
68
70
72
74
YEAR

(d)


CONSTANT 1967 DOLLARS
QUANTITY
VALUE
COMMERCIAL FISH LANDINGS, lb. x 10^6
DOCKSIDE VALUE, $ x 10^6
0
10
20
30
40
50
60
80
0
2
4
6
8
10
12
14
58
60
62
64
66
68
70
72
74
YEAR
(e)

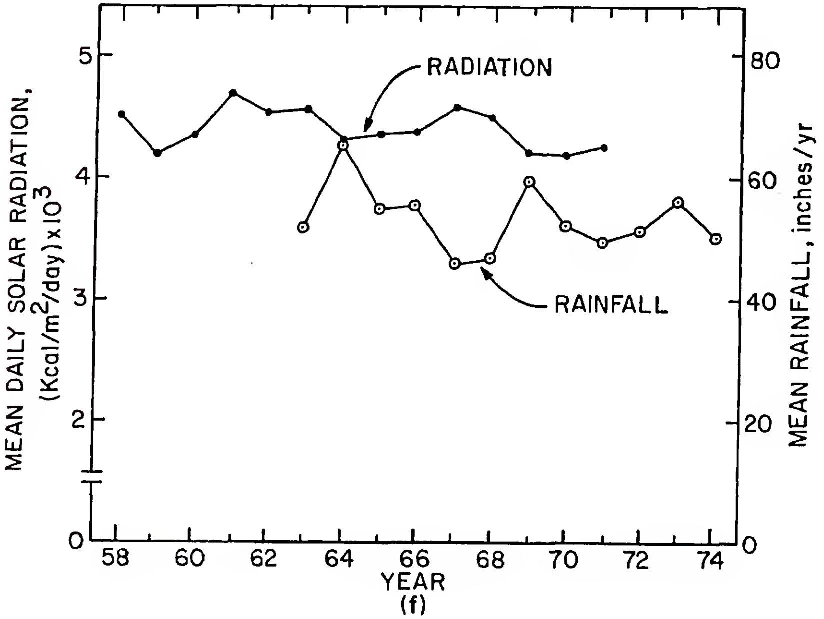

RADIATION
RAINFALL
MEAN DAILY SOLAR RADIATION, (Kcal/m^2/day) x 10^3
MEAN RAINFALL, inches/yr
0
2
3
4
5
0
20
40
60
80
58
60
62
64
66
68
70
72
74
YEAR
(f)

Fig. 18b), has responded during approximately the same period with a phenomenal growth, increasing by 300 percent in 13 yrs. The total personal income during the period from 1960 to 1973 has expanded by about 150% from 2 billion dollars per year to almost 5 billion, corresponding to a 75% increase in average per capita annual income (from $1430 to $2500). In comparison with growth elsewhere in Florida, development in this region had been lagging between 1960-68, but from 1968-73 growth here was almost 7% faster than the state average (see Fig. 18c). The rate of fuel consumption (electricity and gasoline) had about doubled in the 6 yrs from 1967-73, but from 1973-74 the electric use failed to grow and gasoline sales actually declined by 2.5%. This may have been a manifestation of the general recession in the U.S.

Agricultural and fisheries industries, which are more directly dependent on nature, exhibited trends which were markedly different than those of fossil-fuel-intensive industries. Income from agriculture oscillated at about ± 20% of the 14 yr mean (1960-73). However, there has been no long-term pattern of growth or decline in this period and up and down trends never lasted more than about 3 years. Agricultural income in the region, as a percent of the Florida total, grew steadily since 1963 at about 4% per year, possibly reflecting expanded agriculture in the region. Fish harvests similarly showed a fluctuating pattern between 1961-72; however, the amplitude of oscillation was less than for agriculture, being less than 15 percent. From 1965-72 there was a slight decline in total catch (about 3 percent per year), yet the dollar value of the catch has been steadily increasing since 1961 at about 3 percent per year. The primary sources of renewable energy from nature are shown in Fig. 18f. Solar radiation has been relatively steady from 1958-71, with less than 10 percent variation from year-to-year. Rainfall in 1974 was the same as it was in 1961. However, yearly differences in rain are as great as 25 percent during this time period, and peaks and troughs in agricultural income patterns correspond roughly to the rainfall trends. (Compare Figs. 18d and f.)

Ecological and Energy Effects of Power Plant

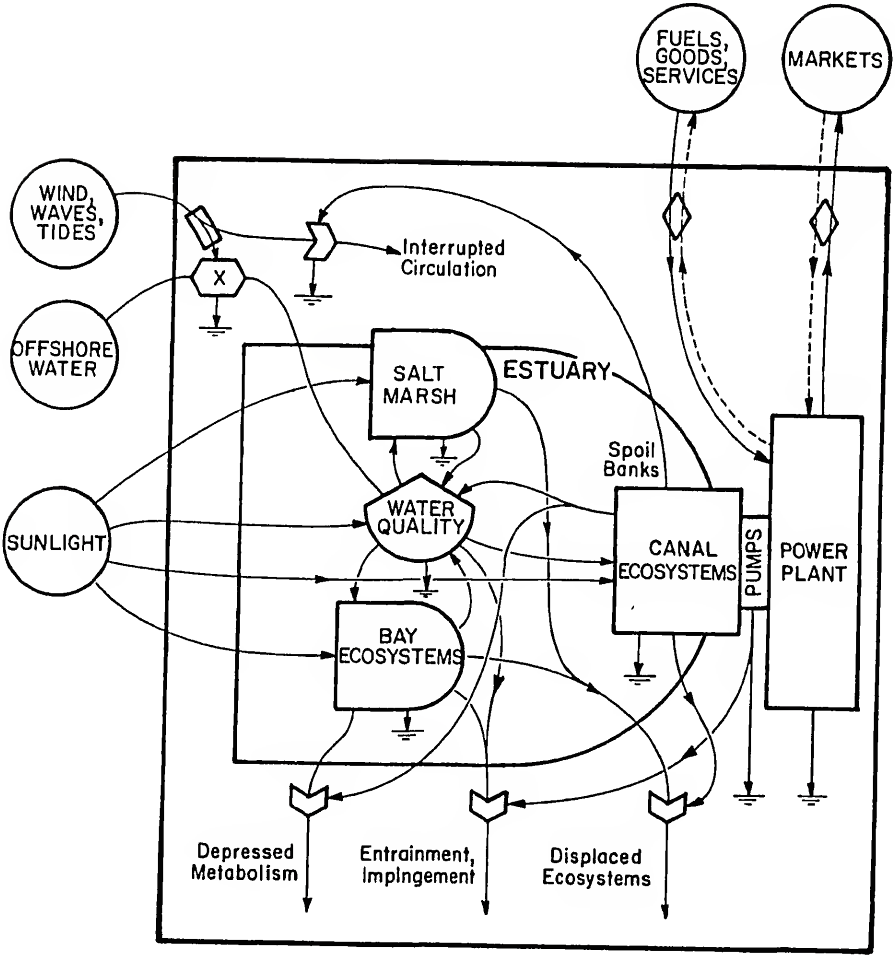
An analysis was done to determine energy equivalents of the impact of Crystal River power plant operation on nearby estuarine ecosystems. A generalized model of major power plant effects on the Crystal River estuarine ecosystem given in Fig. 19 was evaluated with data from different investigators in six main categories: (1) mortality of zooplankton entrained into the power plant circulating water flow; (2) mortality of entrained juvenile fish; (3) mortality of nekton entrapped at the power plant circulation water intake and impinged onto the rotating screens; (4) effects of power plant's waste discharges on receiving-water ecosystems, particularly as manifested in community gross productivity; (5) displacement and replacement of estuarine ecosystems, and resulting changes in productivities; (6) alteration of estuarine hydrodynamics resulting from barracading by canal spoil banks and from the continuous pumping of large volumes of cooling water.

Zooplankton Entrainment

During normal power plant operation units 1 and 2 of the Crystal River plant pump estuarine water at a rate of about 2410 m^3/min. The zooplankton residing in this water are exposed to a sharp temperature rise (ΔT) of about 6°C as the water passes through the power plant condenser tubes. These entrained organisms are subjected to mechanical stress, periodic chlorination, and temperature increase. The addition of a third unit at Crystal River will increase the cooling water flow by about 2580 m^3/min and raise the ΔT to about 8°C.

Standing stocks of various zooplankton populations were taken from

Figure 19. Generalized model of Crystal River estuarine ecosystem depicting major effects of power plant.


FUELS, GOODS, SERVICES
MARKETS
WIND, WAVES, TIDES
X
Interrupted Circulation
OFFSHORE WATER
SALT MARSH
ESTUARY
Spoil Banks
SUNLIGHT
WATER QUALITY
CANAL ECOSYSTEMS
PUMPS
POWER PLANT
BAY ECOSYSTEMS
Depressed Metabolism
Entrainment, Impingement
Displaced Ecosystems

the work of Maturo et al. (1974). Detailed data regarding the mortality rate for copepods passing through the power plant were provided in Alden (1976) and Alden et al. (1976). Mortality rates for other categories of zooplankton, however, were not available. Plankton concentrations were measured in both the intake and discharge canals, and the differences between these measurements might be used to indicate the power plant killing rate. However, as indicated by Maturo et al. (1974) the two canals have distinctively different vertical mixing patterns which render the two sets of samples incomparable. Alternatively, a worst-case assumption of complete (100%) mortality can be used as a conservative upper bound. In this analysis calculations were done using both assumptions, but the latter was used for any comparative purposes.

Plankton data used in analysis of entrainment are summarized in Figs. 20-24. Monthly mean values of copepod standing stocks are given in Fig. 20 for two stations in the intake canal and one at the terminus of the discharge canal. Notice that there was a small decrease in biomass between the two intake stations during the winter months. The difference between the standing stocks in the intake (sta. 4) and discharge were generally about 20-60%. Mortality rates of entrained copepods at Crystal River are summarized in Fig. 21 from the work of Alden (1976). Here, it can be seen that percent mortality ranged from 0 (in December, March and April) to about 80% in late summer. The period of maximum death rate coincided with the times of maximum standing stocks, so that total estimated mortality of copepods reached about 13 x 10^3 m^3 of cooling water flow in September.

Standing stocks of predatory plankton (primarily chaetognaths and

Figure 20. Total copepod standing stocks at three stations in Crystal River study. Figure developed from data of Maturo et al. (1974).

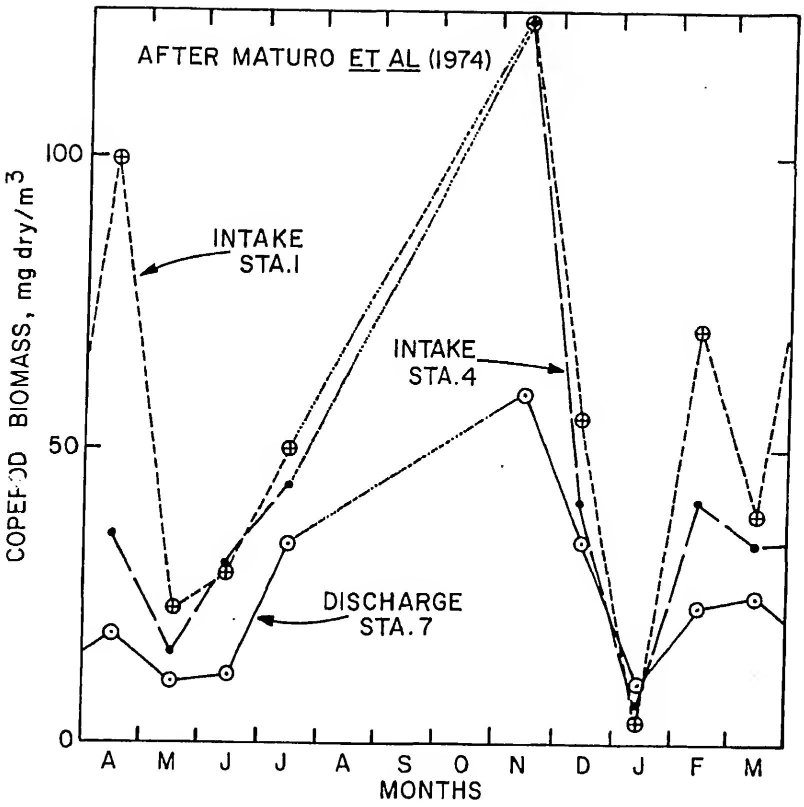

AFTER MATURO ET AL (1974)
INTAKE STA.1
INTAKE STA.4
DISCHARGE STA.7
COPEPOD BIOMASS, mg dry/m3
100
50
0
A
M
J
J
A
S
O
N
D
J
F
M
MONTHS

Figure 21. Proportion of entrained copepods killed and estimated mortality numbers per m^3 of cooling water flow at the Crystal River power plant. Figure developed from data of Maturo et al. (1974) and Alden (1976).

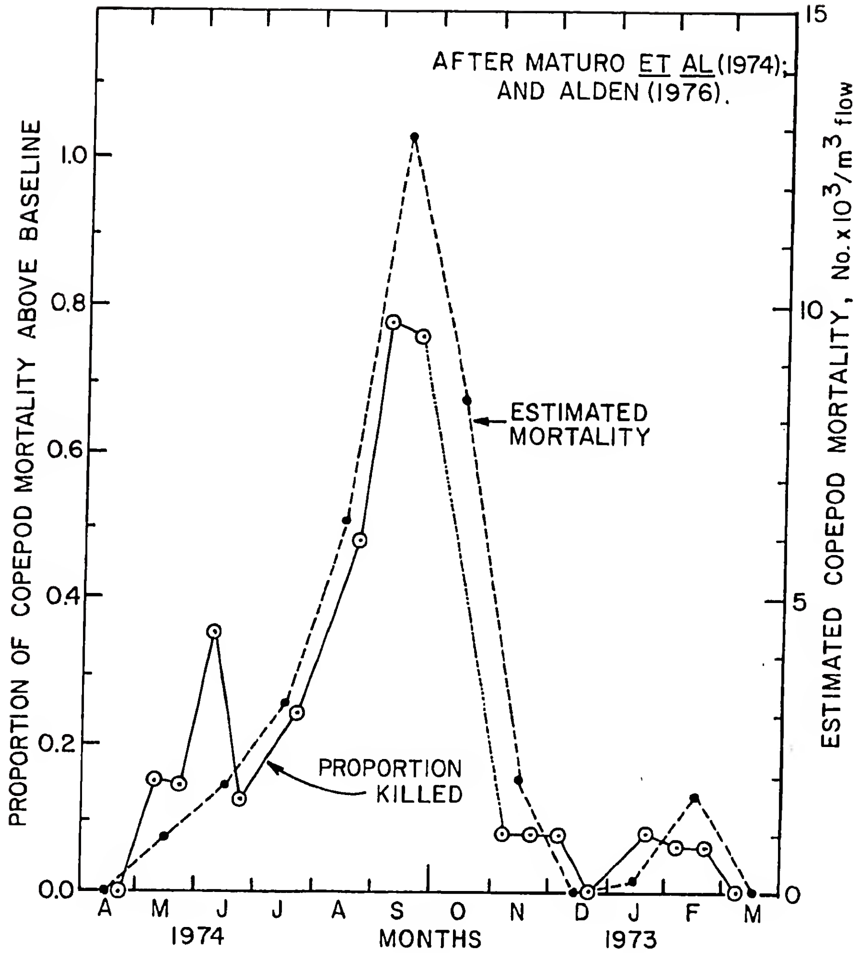

AFTER MATURO ET AL (1974);
AND ALDEN (1976).
PROPORTION OF COPEPOD MORTALITY ABOVE BASELINE
ESTIMATED COPEPOD MORTALITY, No. x 10³/m³ flow
0.0
0.2
0.4
0.6
0.8
1.0
0
5
10
15
ESTIMATED
MORTALITY
PROPORTION
KILLED
A
M
J
J
A
S
O
N
D
J
F
M
1974
MONTHS
1973

Figure 22. Abundance of chaetognaths and medusae in intake and discharge canals at Crystal River power plant. Figure was developed from data of Maturo et al. (1974).

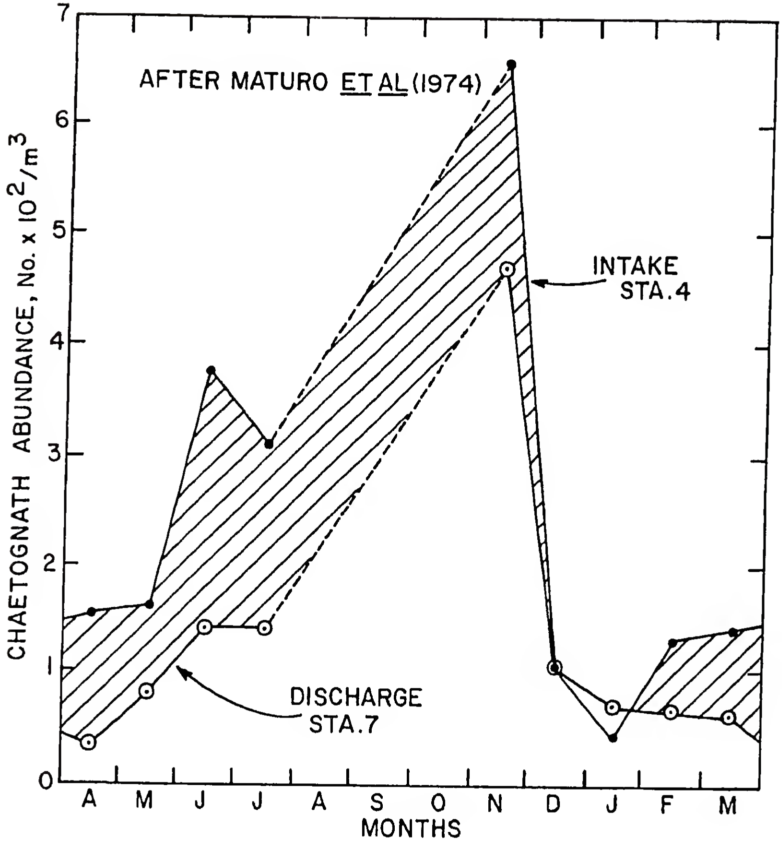

AFTER MATURO ET AL (1974)
CHAETOGNATH ABUNDANCE, No. x $10^2/m^3$
0
1
2
3
4
5
6
7
INTAKE
STA.4
DISCHARGE
STA.7
A
M
J
J
A
S
O
N
D
J
F
M
MONTHS

Figure 23. Total meroplankton abundance in intake and discharge canals at Crystal River power plant. Figure was developed from data of Maturo et al. (1974).

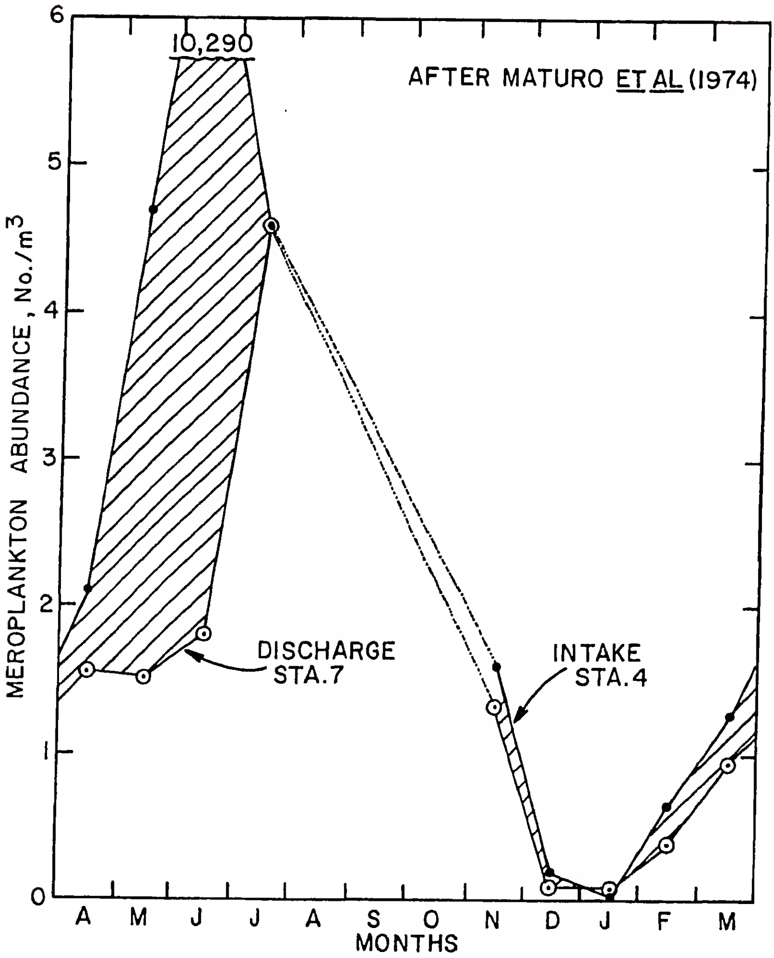
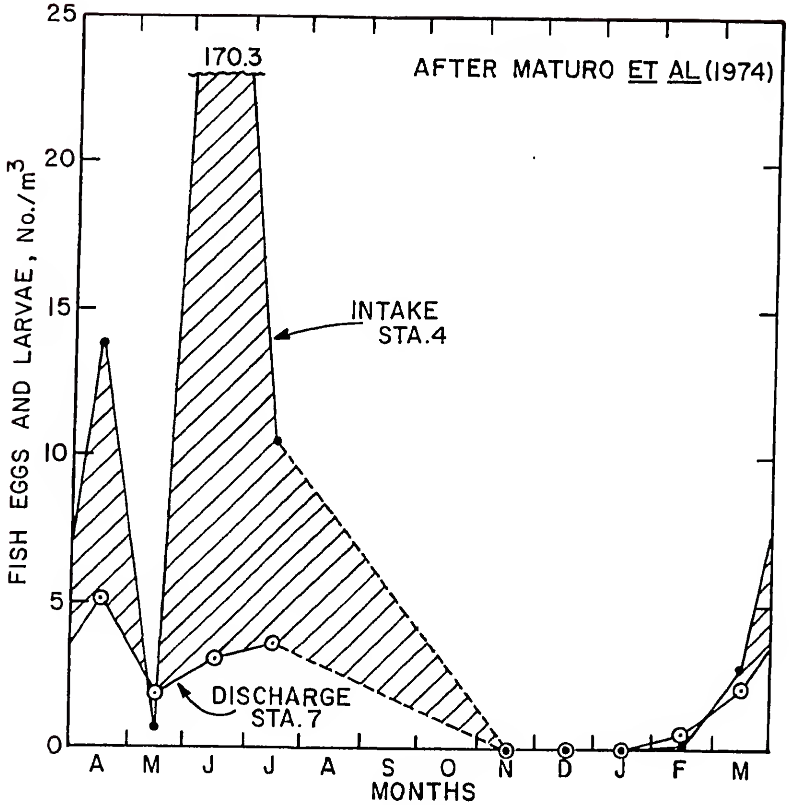

10,290
AFTER MATURO ET AL (1974)
MEROPLANKTON ABUNDANCE, No./m^3
6
5
4
3
2
1
0
DISCHARGE STA.7
INTAKE STA.4
A
M
J
J
A
S
O
N
D
J
F
M
MONTHS

Figure 24. Total abundance of fish eggs and larvae in intake and discharge canals at Crystal River power plant. Figure was developed from data of Maturo et al. (1974).


25
20
15
10
5
0
FISH EGGS AND LARVAE, No./m^3
170.3
AFTER MATURO ET AL (1974)
INTAKE
STA.4
DISCHARGE
STA.7
A
M
J
J
A
S
O
N
D
J
F
M
MONTHS

medusae) are given in Fig. 22. These organisms were separated from the rest of the plankton data because of their higher trophic status as carnivores. Abundance of this group reached a maximum of about $650/m^3$ in November, almost 2 mos after the occurrence of peak copepod populations. The difference between intake and discharge canal populations ranged from 0 (actually < 0) in December and January to about 75% in April. Meroplankton abundance at Crystal River is summarized in Fig. 23. Included in these data are veliger, trochophore, nauplius, cyprid, megalops and zoea stages of various mollusc, crustacean and annelid invertebrates. Here, the difference between intake and discharge canal standing stocks was small (0-30%) for all months except May and June when it approached 85%. As expected for these ephemeral plankton, there was a drastic fluctuation in abundance between seasons. Finally, total abundance of fish eggs and larvae measured in the canals at Crystal River are plotted in Fig. 24. Marked seasonal differences were again observed, ranging from 0 in November through January to $170.3/m^3$ in June. The maximum difference in abundance between intake and discharge stations was 98% in June.

Calculations of the losses of energy value to the estuarine ecosystem resulting from plankton entrainment are given in Tables 13-15. Each of these tables summarizes one of the three different pathways by which energy value was lost from the region. The loss of metabolic work as manifested in production of plankton is summarized in Table 13. Four categories of zooplankton were considered, with the total loss being 140.7×10^6 kcal CE/yr. Of this, 86% is attributable to entrainment of copepods and invertebrate larvae. The loss of potential work for the ecosystem resulting from removal of adult organisms which

Table 13. Loss of energy value associated with plankton entrainment at Crystal River, considering the role of plankton in the estuarine ecosystem.[a]

Organisms	(Q) Water flow, m^3/yr $x10^9$	(C) Plankton population ind/m^3 $x10^3$	(∂) Mortality rate	(m_p) Specific[b] biomass g/ind 10^{-3}	(V_{mp}) Specific[c] production kcal/g·yr	(τ_p) Production[c] time constant· yr	(r_p-r_D) Energy[d] quality loss, CE	(E_p) Energy value, kcalx10^6 CE/yr
Holoplankton	1.27	11.89	0.23	0.0040	62.5	0.08	0.9	62.5
Veligers, Trochopores Zoea	1.27	2.91	1.00	0.0030	65.	0.09	0.9	58.4 (22.7)[e]
Chaetognath, Medusae	1.27	0.30	1.00	0.0035	70.	0.09	2.3	19.3 (8.1)[e]
Fish Eggs and Larvae	1.27	0.018	1.00	0.0030	75.	0.10	0.9	0.5 (0.3)[e]
						TOTAL		140.7 (93.7)[e]

[a] Abbreviations in column headings refer to Eq. (27), Methods Section.

[b] Biomass per organism. Values taken from Maturo et al. (1974).

Table 13. (Continued)

[c] Biomass divided by production. Values estimated from Day et al. (1973).

[d] Energy quality ratios (kcal coal equivalent/kcal organism) calculated by prorating values in Table 38 according to trophic habits of given organism as indicated in Table 39. (See Table 39 for explanation of abbreviations):

Meroplankton & non-predatory holoplankton = Dev(0.45)+Herb(0.4)+FCD(0.10)+FCD(0.05)
= 1.50(0.45)+0.14(0.4)+0.42(0.1)+5.22(0.05)
= 1.03

Chaetognaths & Medusae = Dev(0.1)+Herb(0.1)+FCD(0.4)+FCD(0.4)
= 1.50(0.1)+0.14(0.1)+0.42(0.4)+5.22(0.4)
= 2.42

Detritus = 0.15

[e] Mortality rates estimated from shaded areas in Figs. 16-18 prorate over a 12 month period.

[f] Mean mortality rate for year calculated by multiplying monthly mortality rates times monthly biomass and dividing by the total of all monthly biomass measurements (see Fig. 20).

Table 14. Loss of energy value associated with meroplankton entrainment at Crystal River, considering survival to adulthood and the role of adult organisms in the ecosystem[a].

Organism	(Q) Water flow, m^3/yr $x10^9$	(C) Plankton population ind/m^3	(∂) Mortality rate	(S_A) Natural[b] survival rate $x10^{-3}$	(m_A) Specific[c] biomass, kcal/ind	(r_A) Energy[d] quality ratio, CE	(E_A) Energy value, $kcalx10^6$ CE/yr
Bivalves, Crabs, Polychaets	1.27	2910	1.00	0.008	5.0	1.5	221.7
Fish Eggs, Larvae[e]:							
Leiostomus	1.27	7.6	1.00	0.08	100.0	4.6	355.2
Anchoa	1.27	4.1	1.00	0.08	3.0	4.4	5.5
Gobiosoma	1.27	3.6	1.00	2.7	20.0	4.4	1086.3
Menidia	1.27	1.4	1.00	3.2	8.0	4.6	209.4
Sygnathus	1.27	0.7	1.00	30.0	4.0	5.3	565.4
Bairdiella	1.27	0.6	1.00	0.2	75.0	10.1	115.4
						TOTAL	2558.9

Footnotes to Table 14.

[a] Abbreviations in column headings refer to Eq. (28), Methods Section.

[b] Natural survival rate calculated as = 2/(0.25)f, where f is fecundity. Assumes that there is 25% survival from egg to larval stage (AEC, 1973a), and that on the average each spawn produces 2 adults. The 25% survival estimate is tantamount to an assumption that larvae sampled were 0.5 - 5 mos. old and that sexual maturity is reached at 1 - 3 yrs. Fecundities were taken from Bigelow and Schroeder (1953), AEC (1973a), Norman (1947), Marshall (1966), Homer (Personal Comm.), and Royce (1972), and values used are as follows:

Invertebrates = 1,000,000 eggs/female
Leiostomus = 100,000 "
Anchoa = 100,000 "
Gobiosoma = 3,000 "
Menidia = 2,500 "
Sygnathus = 250 "
Bairdiella = 40,000 "

[c] Specific biomass (g/individual) data taken from Landry (1971), Wagner (1973), and Homer (Personal Comm.).

[d] Energy quality ratios calculated by prorating values in Table 38 according to trophic habits of given organism as indicated in Table 39. (See Table 13, footnote d):

Invertebrates = 1.50(0.6)+0.14(0.3)+5.22(0.1) = 1.46
Leiostomus = 1.50(0.2)+0.42(0.24)+5.22(0.35)+18.17(0.1) = 4.62
Anchoa = 1.50(0.22)+0.42(0.29)+5.22(0.41)+18.17(0.1) = 4.41
Gobiosoma = 1.50(0.2)+0.42(0.24)+5.22(0.48)+18.17(0.08) = 4.36

Footnotes to Table 14. (Continued)

Menidia = $1.50(0.04)+0.42(0.33)+4.22(0.53)+18.17(0.09) = 4.62$

Sygnathus = $0.42(0.33)+5.22(0.48)+1.44(0.05)+18.17(0.14) = 5.26$

Bairdiella = $0.42(0.2)+5.22(0.2)+1.44(0.2)+18.17(0.3)+5.27(0.05)$
$+63.23(0.05) = 10.29$

[e] Assumed that composition of population found by Wilkins et al. (1976) was representative of larval populations at Crystal River.

Table 15. Loss of energy value associated with meroplankton entrainment at Crystal River, considering economic value of surviving adults.[a]

Organism[e]	(Q) Water flow m^3/yr $x10^9$	(C) Plankton population ind/m^3	(∂) Mortality rate	(S_A) Natural[b] survival rate $x10^{-3}$	(m_A) Specific[c] biomass g wet/ind	($d \cdot r_D$) Economic[d] price in energy units kcal CE/g	(E_d) Energy value kcal$x10^6$ CE/yr
Crassostrea American oyster	1.27	182	1.00	0.0004	1.0	27.3	2.5
Peneus Shrimp	1.27	182	1.00	0.0016	3.0	22.0	24.4
Calinectes Blue crab	1.27	182	1.00	0.0016	150.0	5.3	194.0
Menippe Stone crab	1.27	182	1.00	0.0016	50.0	9.7	179.4
Leiostomus Spot	1.27	7.6	1.00	0.08	100.0	4.9	378.4
Anchoa Bay Anchovies	1.27	4.1	1.00	0.08	3.0	1.3	1.6

Table 15. (Continued)

Organism[e]	(Q) Water flow m^3/yr $x10^9$	(C) Plankton population ind/m^3	(∂) Mortality rate	(S_A) Natural[b] survival rate $x10^{-3}$	(m_A) Specific[c] biomass g wet/ind	$(d \cdot r_D)$ Economic[d] price in energy units kcal CE/g	(E_d) Energy value $kcalx10^6$ CE/yr
Menida Silverside	1.27	1.4	1.00	3.2	8.0	2.2	100.1
Bairdiella Silver Perch	1.27	0.6	1.00	0.20	75.0	2.6	29.7
						TOTAL	1010.1

[a] Abbreviations in column headings refer to Eq. (29), Methods Section.

[b] Natural survival rate calculated as $S_A = 2/(0.25)f$, where f is fecundity. Assumes that there is 25% survival from egg to larval stage (AEC, 1973a), and that, on the average, each spawn produces 2 adults. Fecundities taken from Bigdow and Schroeder (1953), AEC (1973a), Norman (1947), Marshall (1966), Day et al. (1973) and Royce (1972), and values used are as follows:

Crassostrea = 20,000,000 eggs/female
Peneus = 5,000,000 "
Calinectes = 5,000,000 "
Menippe = 5,000,000 "
Leistomus = 100,000 "
Anchoa = 100,000 "
Menidia = 2,500 "
Bairdiella = 40,000 "

Table 15. (Continued)

[c] Specific biomass (g/individual) data taken from Landry (1971) for Texas and Snedaker (1974b) for Crystal River.

[d] Prices taken from AEC (1973a) and DMR (1963-73) for dockside values converted to energy units assuming a general ratio of 20,000 kcal CE/$ as indicated by the ratio of total energy input to U.S. economy to the U.S. GNP for 1973 (Kylstra, 1974).

[e] Data taken from Maturo et al. (1974). Assumes that 25% of the invertebrate "meroplankton" larvae are commercially important species and that these are divided equally among 4 categories of commercial invertebrates.

probably would have been produced from entrained meroplankton was calculated in Table 14. Data for invertebrate larvae were aggregated together under the assumption that the trophic habits of these are sufficiently close so that the "quality" of their metabolic energies is similar. A brief description of the species composition of larval fishes encountered at Crystal River by Kreply (1974) was considered inadequate for the purposes of this analysis. Data from a study of the Anclote power plant (about 70 km south of Crystal River) were, therefore, used here to estimate dominant species in fish larvae populations at Crystal River (Wilkins et al., 1976). Similarly, the numbers and species of commercially important invertebrate larvae were not reported by Maturo et al. (1974), and therefore, data from Wilkins et al. (1976) for Anclote were used to characterize the species composition of invertebrate larvae. The total loss of potential work of adult organisms was estimated as 2558.9 x 10^6 kcal CE/yr. Gobies comprise about 42% of this total, while pipefish and spot represent about 22% and 14%, respectively, of the energy loss. The third work pathway lost to the system was calculated in Table 15, where the dockside economic value of fisheries was found equal to about 1010.1 x 10^6 kcal CE/yr. The most important species contributing to this economic and energy impact were spot, blue crabs and stone crabs, representing 37%, 29%, and 18%, respectively, of the economic cost. The total cost of entraining zooplankton, then, is approximately 3.71 x 10^9 kcal CE/yr, and almost 97% of this effect of zooplankton entrainment is attributable to the loss of meroplankton as potential adult organisms functioning in the regional system.

Entrainment of Junveile Fish

In addition to the zooplankton as measured with 64 μ and 202 μ mesh nets, small fry fish (5-50 mm S L) are entrained through the 6.4 mm mesh revolving screens at the power plant intake. These delicate fingerlings are susceptible to high mortality rates as they pass through the power plant pump-condenser system. The rates of juvenile fish entrainment as estimated from 12 diurnal samples at Crystal River between April and September of 1974 are given in Fig. 25 (Snedaker, 1974a). Also shown are occurrences of similar size juveniles in monthly samples of a nearby salt marsh creek (Homer, 1976). Homer's data indicate that Snedaker's samples probably covered the major pulse of the young-of-the year fishes. The average of these 12 samples from Snedaker was thus assumed to represent the mean daily entrainment rates for the 6-8 mo period when a substantial population was present. The data had a mean of 0.66 x 10^6/day and a standard error of 0.12 x 10^6/day (18%).

In Table 16 the energy effect of juvenile fish mortality is estimated on the basis of work done in the ecosystem by these immature organisms. Approximately 90-97% of the total entrainment measurements were comprised of the six species or taxonomic groups listed in the table. Puffers, gobies and burrfish are grouped together assuming that their trophic and breeding characteristics are similar (Bigelow and Schroeder, 1953). The energy quality ratio for metabolism of these juvenile organisms was assumed equal to that of predatory plankton as previously calculated (Table 13). The total energy loss due to entrainment of juvenile fish, then, was 671.7 x 10^6 kcal CE/yr, which is about five times greater than the direct effect of zooplankton mortality by entrainment, but only 18% of the total loss resulting from entrainment

Figure 25. Estimated rates of juvenile fish entrainment at Crystal River power plant and monthly occurrence (in nearby saltmarsh creek) of such juveniles which are susceptible to this entrainment. Figure was developed from data of Snedaker (1974a) and Homer (1976).

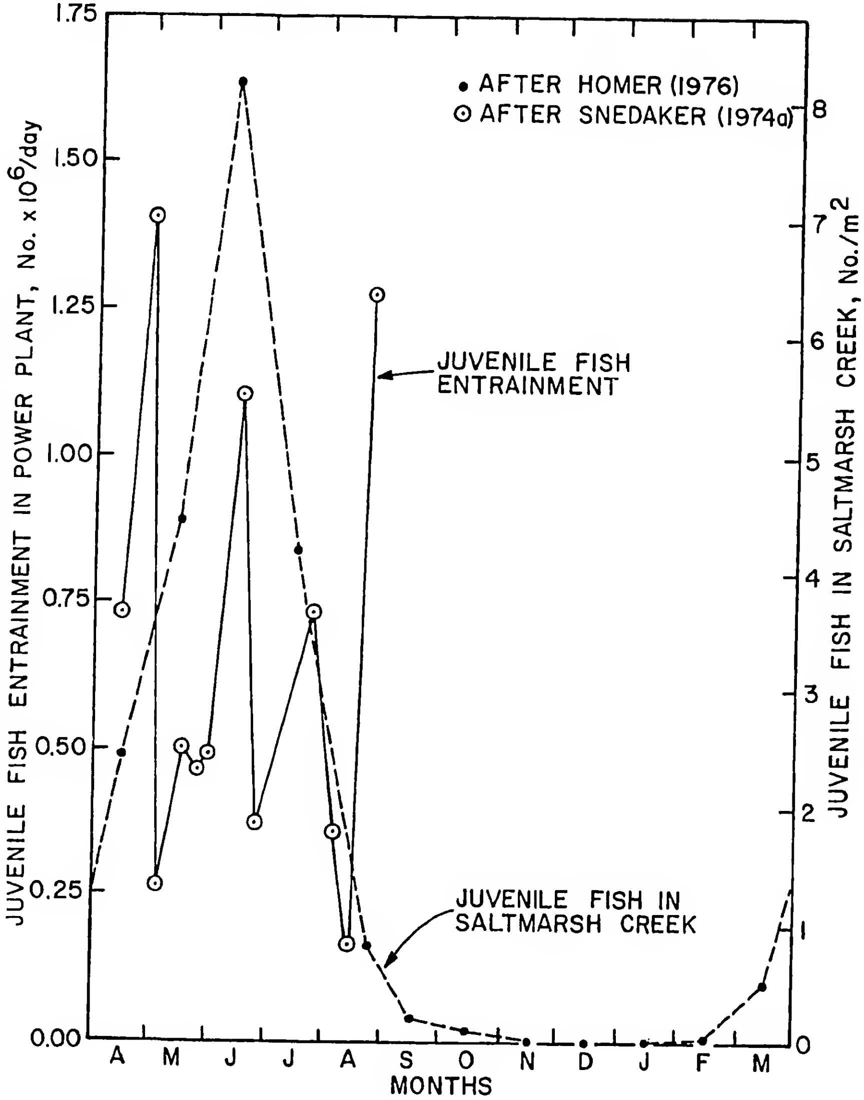

● AFTER HOMER (1976)
⊙ AFTER SNEDAKER (1974a)
JUVENILE FISH ENTRAINMENT
JUVENILE FISH IN SALTMARSH CREEK
JUVENILE FISH ENTRAINMENT IN POWER PLANT, No. x 10^6/day
JUVENILE FISH IN SALTMARSH CREEK, No./m^2
MONTHS
A M J J A S O N D J F M
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
0
1
2
3
4
5
6
7
8

Table 16. Loss of energy value associated with juvenile fish entrainment at Crystal River power plant, considering trophic role of the juveniles in estuarine ecosystem[a]

Organisms	Percent[b] composition of sample	$(Q \cdot C)$ Entrainment[b] rate, no/yr x10^6	(m_j) Specific[c] biomass, kcal/ind.	$(r_j - r_D)$ Energy[d] quality loss CE	(E_j) Energy value loss, kcalx10^6 CE/yr
Anchoa mitchilli Common Anchovie	69	110.2	1.3	2.4	343.8
Opisthonema oglinum Atl. Thread Herring	12	19.2	2.5	2.4	115.2
Menidia beryllina Tidewater silverside	7	11.2	1.6	2.4	43.0
Gobiidae, Diodontidae, Tertadontidae	6	9.6	3.6	2.4	82.9
Prionotus tribulus Bighead searobin	4	6.4	5.5	2.4	84.4
Sygnathus spp. Pipefish	2	3.2	0.3	2.4	2.4
				TOTAL	671.7

Footnotes to Table 16.

[a] Abbreviations in column headings refer to Eq. (27), Methods Section.

[b] Entrainment rate estimated by taking the mean daily rate for 12 samples (Snedaker, 1974a) and dividing by 1.5, assuming that most juveniles are available for entrainment for only 8 months of the year (i.e., they are of the proper size to pass through the intake screens. See Fig. 25). Thus, the total entrainment of juveniles (see Fig. 25) is:

$$(0.66 \times 10^6/\text{day})/1.5 = 0.44 \times 10^6/\text{day} = 160.0 \times 10^6/\text{yr}$$

Data from 4 of the 12 total samples were examined to determine typical species compositions. These were from April, May, July, and August.

[c] Estimates of specific biomass from Homer (Personal Comm.), assuming dry wt. as 20% of fresh weight.

[d] Energy quality ratios calculated by prorating values in Table 38 according to trophic habits of given organism as indicated in Table 39. It is assumed that diet of juveniles corresponds to that of predatory zooplankton (see footnotes to Table 13).

of zooplankton.

As before with the zooplankton calculations (Tables 13-15), the total energy loss was further investigated by considering the potential effect of ultimately reducing populations of adults of a particular species. The ecological work function of these mature organisms is more crucial than that of the juveniles (which occupy a lower trophic position), even though the number of adults surviving from juvenile stages is very small. The total energy loss from entrained juvenile fish, not reaching adulthood to function in their mature ecological role, was only 18.65 x 10^6 kcal CE/yr. This was over two orders-of-magnitude less than the total loss from zooplankton mortality. The economic value of these potential adults was estimated to be still an order-of-magnitude less than the above figure and was therefore not included in the totals (Table 17).

Impingement of Nekton

The normal operation of steam electric power plants with once-through cooling water systems generally results in the continual capturing of large swimming organisms (nekton) at the water intake point. These nekton are entrapped in the swift currents at the intake and are impinged on the 6.4 mm screens which keep circulating water to the condensers free of large objects. At Crystal River the screens rotate on an axis perpendicular to the direction of water flow, and fish and debris are washed from the screens into a trough, through which they are sluiced to a wire basket of about 8 m^3 volume. The basket contents, including dead organisms are dumped approximately once per week in a designated area adjoining the nearby salt marsh.

Table 17. Loss of energy value associated with entrainment of juvenile fish at Crystal River power plant, considering survival to adulthood and the role of adult organisms in the ecosystem.

Organism[e]	($Q \cdot C$) Entrainment[a] rate, no/yr x10^6	(S_A)[b] Natural survival rate x10^{-3}	(m_A) Adult biomass, kcal/ind	(r_A)[d] Energy quality loss, CE	(E_j) Energy value loss kcalx10^6CE/yr
Anchoa mitchilli Common Anchovie	110.2	0.18	3	4.4	0.26
Opisthonema oglinum Atl. Thread Herring	19.2	0.88	15	4.0	1.01
Menidia beryllina Tidewater Silverside	11.2	3.03	8	4.6	1.25
Gobiidae, *Diodontidae*, *Tetradontidae*	9.6	7.36	20	4.4	6.22
Prionotus tribulus Bighead Searobin	6.4	2.56	100	5.2	8.52
Sygnathus spp. Pipefish	3.2	20.5	4	5.3	1.39
				TOTAL	18.65

---

[a] Abbreviations in column headings refer to Eq (28), Methods Section.

[b] Natural survival rate calculated from Eq (30), Methods Section. This equation assumes an exponential mortality rate between hatch and sexual ripening of the offspring. The survival rate from a given juvenile stage to adulthood is estimated from Eq (31), Methods Section.

Table 17. (Continued)

Survival, S_j, is calculated from data given by same references as Table 14 footnotes (primarily Bigelow and Schroeder, 1953):

Anchoa: $f = 100{,}000$; $a = 3.5$ yr; $t_j = 8$ mo. (0.67 yr); $S_j = 0.18 \times 10^{-3}$

Opisthonema: $f = 30{,}000$; $a = 3$ yr; $t_j = 9$ mo. (0.74 yr); $S_j = 0.88 \times 10^{-3}$

Gobiidae, etc.: $f = 3{,}000$; $a = 1$ yr; $t_j = 0.3$ yr; $S_j = 7.36 \times 10^{-3}$

Prionotus: $f = 10{,}000$; $a = 3$ yr; $t_j = 10$ mo. (0.83 yr); $S_j = 2.56 \times 10^{-3}$

Sygnathus: $f = 250$; $a = 1$ yr; $t_j = 2$ mo. (0.17 yr); $S_j = 20 \times 10^{-3}$

Menidia: $f = 2500$; $a = 1$ yr; $t_j = 2$ mo. (0.17 yr); $S_j = 3.03 \times 10^{-3}$

[c] From Snedaker (1974b), Landry (1971), Wagner (1973), and Homer (Personal Comm.).

[d] See footnote (d), Tables 13 and 14:

Opisthonema: $r_A = 1.50(0.25)+5.22(0.4)+0.42(0.27)+18.17(0.08) = 4.03$

Prionotus: $r_A = 0.42(0.28)+5.22(0.58)+18.17(0.11)+1.44(0.03) = 5.19$

[e] See footnote (b), Table 16.

Nekton impingement data from Crystal River are summarized in Fig. 26. Generally, the impingement rate increased inversely with temperature, peaking in February; however, an inordinate pulse of migrating Atlantic threadfin in May caused the impingement in that month to be well above the winter level. It is apparent in this figure that week-to-week variability in the samples was substantial. It is estimated that a total of 26.7 x 10^3 kg (fresh) of animal biomass was killed by impingement in the 12 mos from August, 1972 to August, 1973.

Energy value losses from the estuary resulting from power plant operation are summarized in Table 18, where the 14 dominant species or taxa encountered in the impingement study are listed, representing over 96% of the total biomass sampled. Energy quality ratios were calculated, referring to Tables 38 and 39, and it was found that several relatively high-quality species were killed by impingement (including Loligo: 16.0 times the quality of coal; Caranx: 14.9; and Lagodon: 11.9). The energy loss to the estuary resulting from killing these nekton was estimated to be 147.6 x 10^6 kcal CE/yr (Table 18). This is only about 4% of the total energy cost of zooplankton entrainment (Tables 13-15) and some 23% of the loss resulting from entrainment of juvenile fish (Tables 16 and 17).

Calculations of potential economic value lost due to impingement of nekton are summarized in Table 19. Generally, the most commonly impinged fish (Table 18) were not the most economically valuable, and it is seen in Table 19 that only about 12% of the total impinged biomass was made up of economically important species. The total potential economic loss resulting from impingement of nekton at Crystal River was estimated in energy terms to be only 16.8 x 10^6 kcal CE/yr. This is

Figure 26. Rate of impingement of nekton at power plant intake screens. Large open bars are mean weekly impingement rate as measured by Snedaker (1974b) for Crystal River. Cross-hatched bars represent one standard error of this mean rate, and numbers above bars indicate number of measurements used to calculate mean rate.

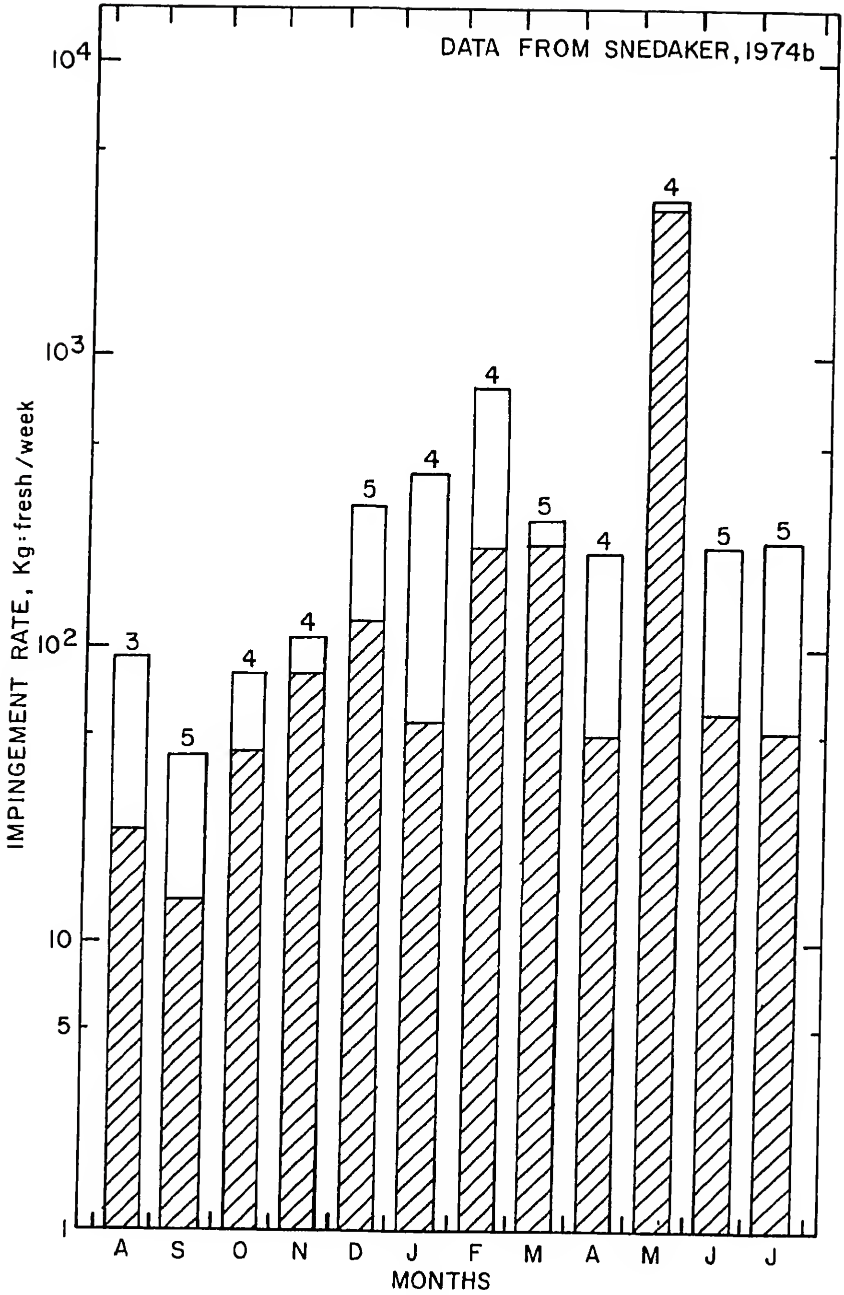

DATA FROM SNEDAKER, 1974b
IMPINGEMENT RATE, Kg: fresh / week
10^4
10^3
10^2
10
5
1
3
5
4
4
5
4
4
5
4
4
5
5
A
S
O
N
D
J
F
M
A
M
J
J
MONTHS

Table 18. Energy calculation of value loss resulting from impingement of nekton at the cooling water intake of the Crystal River power plant, considering the trophic roles of organisms in the estuarine ecosystem[a].

Organism	Percent composition of sample	Stocks impinged, kcalx10^6/yr	$(r_A - r_D)$[c] Energy quality loss	(E_A) Energy value, kcalx10^6 CE/yr
Polydactylus octonemus Atlantic Threadfin	51.9	13.23	3.7	49.0
Ogcocephalus radiatus Polkadot Batfish	26.7	6.79	8.9	60.4
Chilomycterus schoepfi Striped Burrfish	6.1	1.56	5.8	9.1
Calinectes sapidus Blue Crab	3.9	0.99	5.9	5.8
Lactophyrus quadricornis Scrawled Cowfish	1.9	0.49	8.9	4.4
Ascidiacea Tunicates	1.6	0.41	1.6	0.7
Lagodon rhomboides[b] Pinfish	1.6	0.40	11.7	4.7
Eucinostomus gula[b] Silver Jenny	1.5	0.37	4.4	1.6

Table 18. (Continued)

Organism	Percent composition of sample	Stocks impinged, kcalx10^6/yr	$(r_A - r_D)$ Energy[c] quality loss	(E_A) Energy value, kcalx10^6 CE/yr
Loligo spp.[b] Squid	1.3	0.32	15.8	5.1
Bairdiella chrysura[b] Silver Perch	1.1	0.29	10.1	2.9
Harengula pensicolae[b] Scaled Sardine	1.0	0.26	4.5	1.2
Caranx hippos[b] Crevalle jack	0.6	0.16	14.8	2.4
Mugil cephalus[b] Striped mullet	0.4	0.11	1.0	0.1
Peneus spp. Shrimp	0.4	0.09	1.8	0.2
TOTALS	100.0	25.47		147.6

[a] Standing stocks are taken from Snedaker (1974b), based on weekly samples from 13 Aug., 1972 to 3 Aug., 1973. Assumes dry wt = 20% of fresh wt. and 5 kcal/g dry matter. Abbreviations for column headings refer to Eq. (32), Methods Section.

Table 18. (Continued)

[b] To be conservative, total weekly biomass measurements for these species were multiplied times 2 screens times 7 days per week, rather than times 7.66 as indicated by statistical model in Snedaker (1974b).

[c] Energy quality ratios calculated (as before) by prorating values in Table 38 according to trophic habits of given organisms as indicated in Table 39:

Polydactylus = 1.50(0.25)+0.42(0.22)+5.22(0.45)+18.17(0.08) = 3.80

Ogcocephalus = 0.42(0.22)+5.22(0.51)+18.17(0.17)+1.44(0.05)+63.23(0.05) = 9.08

Chilomycterus =0.44(0.22)+5.22(0.51)+18.17(0.17)+1.44(0.05)+63.23(0.05) = 9.08

Lactophyrus = 0.44(0.22)+5.22(0.51)+18.17(0.17)+1.44(0.05)+62.23(0.05) = 9.08

Lagodon = 0.44(0.08+5.22(0.34)+18.17(0.33)+1.44(0.19) = 63.23(0.06) = 11.87

Eucinostomus = 1.50(0.12)+5.22(0.49)+0.42(0.3)+18.17(0.09 = 4.50

Bairdiella = 0.42(0.2)+5.22(0.2)+18.17(0.3)+1.44(0.2)+63.23(0.05)+5.27(0.05) = 10.29

Harengula = 5.22(0.52)+0.42(0.38)+18.17(0.1) = 4.69

Caranx = 5.22(0.14)+18.17(0.48)+1.44(0.3)+63.23(0.08) = 14.94

Mugil = 1.50(0.75)+0.14(0.25) = 1.16

Loligo = 5.22(0.19)+0.42(0.08)+18.17(0.39)+1.44(0.22)+63.23(0.12) = 16.02

Peneus = 1.50(0.48)+0.14(0.2)+5.22(0.22)+0.42(0.1) = 1.94

Table 18. (Continued)

Calinectes = 1.50(0.24)+5.22(0.35)+0.42(0.15)+18.17(0.2)+1.44(0.06) = 5.97

Ascidiaceae = 1.50(0.5)+0.14(0.3)+5.22(0.1)+0.42(0.08)+18.17(0.02) = 1.71

DETRITUS = 0.15

Table 19. Energy calculation of value loss resulting from impingement of nekton at the cooling water intake of the Crystal River power plant, considering the direct monetary value to the regional economy.[a]

Organisms	Percent composition of total impingement sample	(M) Biomass[b] entrapped, (g wet)x10^6/yr	($d \cdot r_d$) Economic price in energy units kcal CE/g	(E_D) Energy value, kcalx10^6 CE/yr
Calinectes sapidus Blue Crab	3.9	0.99	5.3	5.3
Lagodon rhomboides Pinfish	1.6	0.40	3.4	1.4
Eucinostomus gula Silver Jenny	1.5	0.37	4.9	1.8
Loligo spp. Squid	1.3	0.32	7.1	2.3
Bairdiella chrysura Silver Perch	1.1	0.29	2.6	0.8
Harengula pensicolae Scaled Sardine	1.0	0.26	2.6	0.7
Caranx hippos Crevalle Jack	0.6	0.16	2.6	0.4

Table 19. (Continued)

Organisms	Percent composition of total impingement	(M) Biomass[b] entrapped (g wet)x10^6/yr	($d \cdot r_d$) Economic price in energy units kcal CE/g	(E_D) Energy value, kcalx10^6 CE/yr
Mugil cephalus Striped Mullet	0.4	0.11	4.9	0.5
Peneus spp. Shrimp	0.4	0.09	39.7	3.6
TOTALS	11.8	2.99		16.8

[a] Includes only impinged nekton with economic value as fishery. Abbreviations in column headings refer to Eq. (33), Methods Section.

[b] See note (b) Table 18.

[c] Prices taken from AEC (1973a) and DMR (1963-1973) for dockside values; converted to energy units assuming a general ratio of 20,000 kcal CE/$ as indicated by the ratio of total energy input to the U.S. economy to the U.S. GNP for 1973 (Kylstra, 1974).

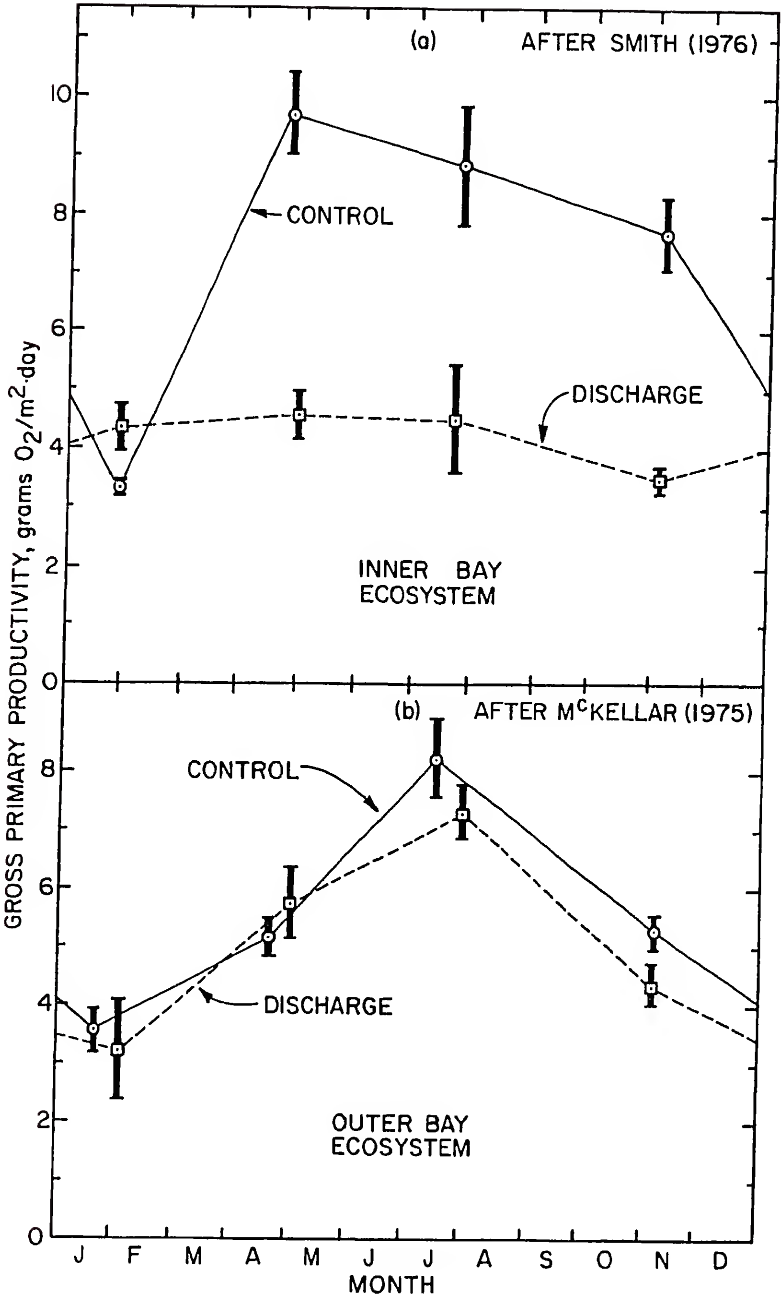
about 11% of the energy value of the ecological work done by these same animals, and is less than 2 percent of the economic loss from zooplankton entrainment.

Effects of Power Plant Wastes on Ecological Productivity

Phytoplankters that traverse the journey through power plant condensers are subjected to the same kinds of physical, thermal, and chlorine stresses as are entrained zooplankton, and it would be expected that their metabolic functions (production and respiration) as they flow out into the estuary might be altered in some way. At Crystal River the benthic, macrophte-dominated ecosystems surrounding the point of cooling water discharge, are also exposed to thermal influences, as well as possible reduced availability of light due to increased silt and seston concentration in the discharge water. Since primary productivity and respiration are measures of biological work done in the ecosystem, any changes in these metabolic functions resulting from power plant discharges can be monitored or otherwise estimated, and these data can be used as an index of the energy effects of power plants on estuaries.

Measurements of gross primary productivity by Smith (1976) and McKellar (1975) for the bay ecosystems at Crystal River are summarized in Fig. 27. There was a marked difference between the inner bay (Fig. 27a) productivities at the control site and at the site receiving power plant discharges (43% reduction). Productivity in the outer bay was less affected by power plant discharges than was a control area (Fig. 27b). Under control conditions the inner bay was considerably more productive (annual mean $\doteq$ 7.38 g $O_2/m^2 \cdot$day compared to 5.58) than the outer bay, yet it suffered greater effects from the power plant

Figure 27. Gross primary productivity estimates for (a) inner and (b) outer bay ecosystems at Crystal River, as inferred from measurements of diurnal changes in dissolved oxygen (Smith, 1976; McKellar, 1975). Points represent seasonal means and bars indicate ±1 standard error of the means.


(a) AFTER SMITH (1976)
CONTROL
DISCHARGE
INNER BAY ECOSYSTEM
(b) AFTER McKELLAR (1975)
CONTROL
DISCHARGE
OUTER BAY ECOSYSTEM
GROSS PRIMARY PRODUCTIVITY, grams O2/m2·day
0
2
4
6
8
10
J
F
M
A
M
J
J
A
S
O
N
D
MONTH

discharges. The negative effect of power plant discharges was greatest in the warm months for both inner and outer bay ecosystems, with productivities of the discharge areas actually stimulated above control levels during the winter for inner bay and early spring for outer bay. Maximum productivity of the shallow inner bay coincided with maximum sunlight during the late spring; however, peak production in the plankton-dominated outer bay occurred (along with maximum temperatures) in the summer.

Net and gross primary production measurements by Young (1974a, b) for the salt marsh ecosystems at Crystal River are given in Fig. 28 for stands dominated by Juncus roemarianus (Fig. 28a) and by Spartina alterniflora (Fig. 28b). Net productivities, as indicated by changes in standing stocks, exhibited marked seasonal attributes with summer maxima and winter values going to zero. Values were well below measurements of gross production except the summer data for Juncus at control site, where net and gross were nearly identical. Unfortunately, only winter and summer measurements of gross productivity were available; however, control values for Juncus were found to be statistically higher than discharge values in both seasons, while Spartina production was significantly higher in the control ecosystem during the winter, although there was no significant difference in the summer.

The energy impact of power plant discharges on the Crystal River estuarine ecosystem, as indicated by changes in gross productivity, is given in Table 20. The differences between annual mean values for productivity in control and discharge ecosystems were assumed (conservatively) to be attributable in some way to the effects of power plant waste discharges. Mean annual productivities were reduced 43%,

Figure 28. Net and gross primary productivity estimates for salt marsh ecosystems at Crystal River, *Juncus* (a) and *Spartina* (b). Net productivities (NPP) were calculated from data of Yount (1974b) considering changes in standing stocks. Gross productivity (GPP) was estimated with CO_2 infrared gas analysis by Young (1974a, b).

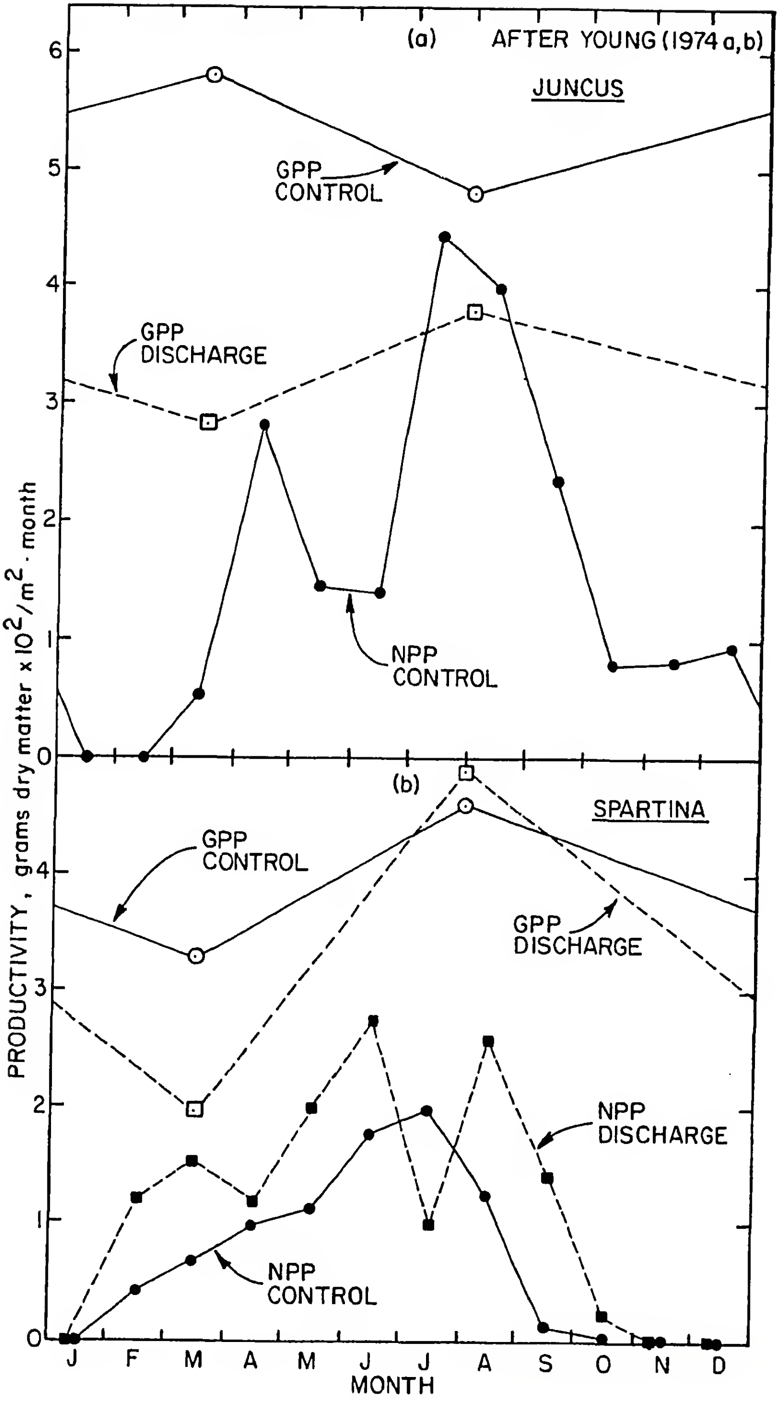

(a)
AFTER YOUNG (1974 a,b)
JUNCUS
GPP CONTROL
GPP DISCHARGE
NPP CONTROL
(b)
SPARTINA
GPP CONTROL
GPP DISCHARGE
NPP DISCHARGE
NPP CONTROL
PRODUCTIVITY, grams dry matter × 10²/m² · month
0
1
2
3
4
5
6
J
F
M
A
M
J
J
A
S
O
N
D
MONTH

Table 20. Estimates of the energetic impact of discharges from Crystal River power plant Units 1 and 2 on the surrounding ecosystems, as indicated by changes in community gross primary productivity.

Ecological Subsystem	$(P_G \cdot \partial_M \cdot r_M)$[a] changes in gross productivity, kcal CE/m^2·yr	(A) Affected[b] area $m^2 x10^6$	(E_M) Energy value loss kcal CEx10^6/yr
Inner Bay[c]			
Control	673		
Discharge	386		
Change	287	0.93	267
Outer Bay[d]			
Control	509		
Discharge	476		
Change	33	1.81	60
Salt Marsh[e]			
Juncus			
Control	1570		
Discharge	985		
Change	585	0.76	445
Spartina			
Control	1165		
Discharge	1004		
Change	161	0.19	31
TOTAL CHANGE		3.69	803

[a] Abbreviations in column heading refer to Eq. (34), Methods Section. Energy quality ratio, r_M, for gross productivity is from Odum *et al.* (1975).

[b] Affected area, A, taken from Table 21.

[c] Smith (1976).

[d] McKellar (1975).

[e] Productivity data from Young (1974b). Areas estimated from Klausewitz *et al.* (1974), assuming 20% *Spartina* and 80% *Juncus* (Young, personal comm.).

6%, 37%, and 14% for the inner bay, outer bay, Juncus marsh and Spartina marsh, respectively. Areas of the inner and outer bays were found to closely coincide with the areas enclosed in the 3°C and 1.5°C isotherms (respectively) of the thermal plume as mapped by Klausewitz (1973). These calculated areas are given in Table 21 for measured conditions of power plant units 1 and 2 operating and predicted conditions for units 1-3. A third region (that within the 5°C ΔT isotherm) was calculated for the conditions with units 1-3, and the effects of these more extreme temperatures was investigated with simulations of an ecological model (see Fig. 69). The salt marsh areas affected by power plant effluent were computed from thermal maps developed by Klausewitz et al. (1974), assuming a 4:1 ratio of Juncus to Spartina area coverage as indicated by Young (personal comm.).

The total energy effect of these discharges on the ecological productivity of systems receiving thermal wastes amounts to about 803×10^6 kcal CE/yr. Most of this impact is absorbed by the inner bay and Juncus marsh systems. Further effects resulting from the addition of Unit 3 were estimated in Table 22. Predictions of the increased plume size (Klausewitz, 1973; Florida Power Corp., 1974) were used to estimate the extended influence of power plant discharges. The energy effect with Unit 3 operating was thus calculated to be 1487×10^6 kcal CE/yr (Table 22), or 46% greater than previously (Table 20). Once again, the inner bay (including the added effect of a +5°C ΔT isotherm) and Juncus marsh were found to be most affected by this stress.

Displacement and Replacement of Ecosystems

Construction of the Crystal River power plant and its ancillary

Table 21. Estimated size of discharge plume from Crystal River power plant.[a]

Range of Temperature Increment Between Isotherms, °C	Area Within Isotherms, $m^2 x 10^6$					
	Units 1 and 2 Operating			Units 1, 2 and 3 Operating		
	Flood Tide	Ebb Tide	Mean Tide	Flood Tide	Ebb Tide	Mean Tide
5-7	---	---	---	0.31	0.36	0.34
3-5	0.86	1.09	0.93	1.21	1.53	1.37
1.5-3	2.30	1.32	1.81	4.01	2.30	3.15
Total Area	3.16	2.41	2.74	5.53	4.19	4.86

[a] Areas were estimated from field data and model predictions of Klausewitz (1973) and from other analyses given in Florida Power Corp. (1974). Areas measured by planimeter with linear interpolation.

Table 22. Estimates of the energetic impact of discharges from Crystal River power plant Units 1, 2 and 3 on the surrounding ecosystems, as indicated by changes in community gross primary productivity.

Ecological Subsystem	Control Productivity kcal CE/$m^2 \cdot$yr	Fractional Change	Area[a] Affected, $m^2 x 10^6$	E_M, Energy Value loss, kcal CE$x10^6$/yr
Inner Bay[b]				
Within 5 C Plume	673	0.68[d]	0.34	156
Within 3-5 C Plume	673	0.43	1.37	396
Outer Bay[b]	509	0.06	3.15	96
Salt Marsh[c]				
Juncus	1570	0.37	1.35	784
Spartina	1165	0.14	0.34	55
TOTAL CHANGE			6.55	1487

[a] Values computed in Table 21.

[b] Data from Smith (1976) and McKellar (1975). See Fig. 27.

[c] Productivity values from Young (1974b). Areas are estimated assuming same percent change (with addition of Unit 3) as calculated in Table 21.

[d] Effect of discharge on estuarine productivity computed with simulation of ecosystem model in this study (see Fig. 75)

circulating-water-system has itself created a substantial impact on the local, natural ecosystems which have been displaced by power plant facilities. Because construction has been taking place on site almost continuously since the first ground was turned in the early 1960's, a vast area (nearly 1 km^2) of natural land has been out of production for almost 15 years. When the cooling water canals were dredged, large strips of marsh and bay were also displaced, but these have since been replaced by canal ecosystems.

The energetic impact of displacing these ecosystems was calculated in Table 23. The ecosystems, which have developed in the canals were relatively productive, being intermediate between bays and marshes; however, the ecosystems of the canal spoil banks were sparsely vegetated and were assumed to be relatively unproductive. The net effect of dredging the canals on ecological productivity was, thus, computed to be a loss of 757 x 10^6 kcal CE/yr. Construction of the principal power plant facilities resulted in an estimated annual loss of productivity amounting to 1488 x 10^6 kcal CE. Including this figure in the calculation of construction impact brings the total net loss to 2245 x 10^6 kcal CE/yr. This is almost 3 times as large as the effect of power plant discharges (Table 20). The addition of unit 3 to the power plant system was found to increase the total construction impact by only 22% to 2737 x 10^6 kcal CE/yr.

Effects on Estuarine Hydrodynamics

The peninsular and island chain formed by dredge spoils from construction of cooling water canals at Crystal River extends some 13.4 km

Table 23. Estimates of energetic impact of displacing and replacing ecosystems by construction associated with power plant at Crystal River[a]

Ecological Subsystem	($P_G \cdot r_M$) Gross Primary Productivity kcal CE/m^2/yr	A Affected Area m^{2}x10^6	E_M Energy Value Loss kcal CEx10^6/yr
DISPLACED (-)			
By Canals:			
Inner Bay	673[b]	0.388[f]	261
Outer Bay	509[b]	1.384[f]	704
Marsh - *Juncus*	1570[b]	0.439[g]	689
Marsh - *Spartina*	1165[b]	0.109[g]	127
By Power Plant:			
Marsh - Units 1 & 2	1489[c]	0.999[h]	1488
(Marsh - Units 1-3)	(1489[c])	(1.330[h])	(1980)
Total Displacement		3.319	-3269
(with Unit 3)		(3.650)	(-3761)
REPLACED (+)			
Intake Canal	678[d]	1.140[f]	773
Discharge Canal	750[d]	0.219[f]	164
Canal Spoil Banks	91[e]	0.961[f]	87
Total Replaced		2.320	+1024
NET TOTAL EFFECT			-2245 (-2737)

---

[a] Abbreviations in column headings refer to Eq. (34), Methods Section.

[b] Productivity estimates from Smith (1976), McKellar (1975) and Young (1974b) for inner and outer bays and marsh, respectively.

[c] General productivity for marsh estimated by prorating values for *Spartina* and *Juncus*, 1:4 (Young, personal comm.).

[d] Productivity measurement made in this study, see Table 27.

[e] Assumed same as productivity of dune vegetation as estimated in Odum and Brown (1975).

Table 23. (Continued)

[f] Areas calculated from maps given in Carder *et al.* (1974).

[g] Areas estimated from isotherm maps developed by Klausewitz *et al.* (1974).

[h] Areas computed from aerial photographs and maps given in AEC (1972b), coupled with ground observations.

into the Gulf of Mexico. These spoil banks divert long-shore movements of water around their extremity and through small passes between the spoil islands which begin (beyond where the peninsula breaks) at about 7.4 km offshore. These sand and limestone talus mounds (which set about 4 m above MSL) also reduce the effect of wind mixing in the adjacent bay waters by shielding them from winds. It was assumed that the frictional drag created by these banks on longshore currents had the effect of diverting the water's kinetic energy from its normal transport work into erosion work done on the banks' structure (Klausewitz, personal comm.). The power plant, however, returns some of this lost kinetic energy by continuously pumping cooling water through its canals. In this section, calculations are made to compare these alterations of hydrodynamic energy.

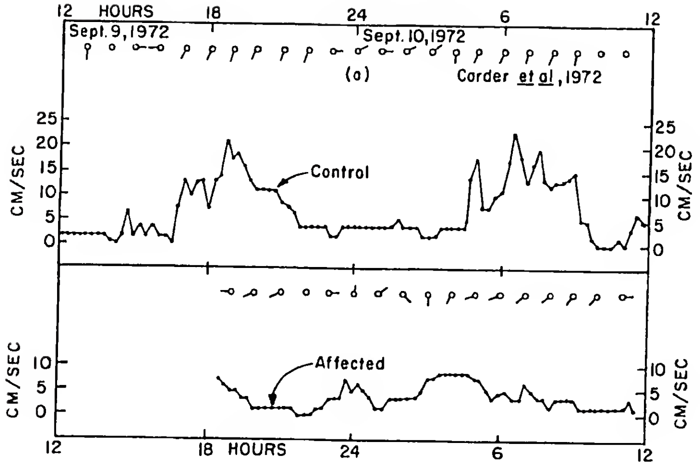
The normal transport work of these estuarine waters was assumed to be a function of both (1) advective flow and (2) turbulent flow as expressed in the diffusion equation (O'Brien and Wroblewski, 1973),

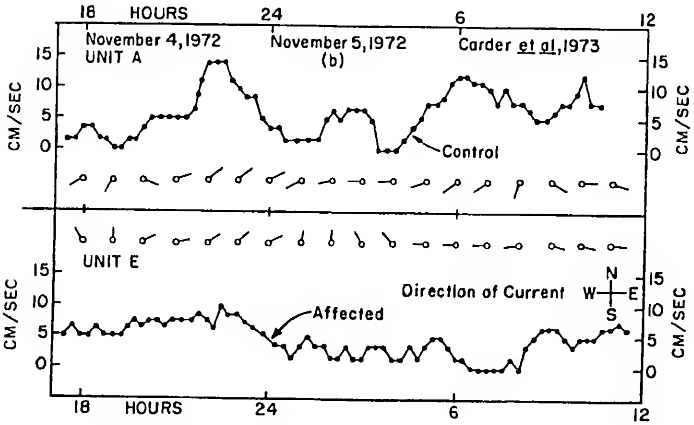
$$\frac{\partial N}{\partial t} = -u \frac{\partial N}{\partial L} + K \frac{\partial^2 N}{\partial^2 L} \qquad (40)$$

where N is material being transported, u is mean velocity, L is distance along gradient of N, and K is eddy viscosity.

In Fig. 29 time series of tidal and wind-induced current measurements are given, comparing areas in close proximity of the spoil banks (< 300 m) with areas about 3 km from the banks. Changes in the first term on the right-hand side of equation (40) were accounted for by comparing the difference in kinetic energies of waters within and away from the influence of canal spoil banks. The mean current speed for the

Figure 29. Time series of current measurements at Crystal River comparing areas away from and within the influence of canal spoil banks. (a) Data from September 9-10, 1972. (b) Data from November 5, 1972.


12 HOURS 18 24 6 12
Sept. 9, 1972
Sept. 10, 1972
(a)
Corder et al, 1972
CM/SEC
0 5 10 15 20 25
Control
Affected
0 5 10
12 18 HOURS 24 6 12


18 HOURS 24 6 12
November 4, 1972
UNIT A
November 5, 1972
(b)
Carder et al, 1973
CM/SEC
0 5 10 15
Control
UNIT E
Direction of Current
N
W
E
S
Affected
18 HOURS 24 6 12

affected stations were 3.96 and 4.59 cm/sec on 9-10 September and 4-5 November 1972, respectively, compared to 7.97 and 6.02 cm/sec, respectively for the uninfluenced stations. The kinetic energies were calculated by

$$E_k = \frac{1}{2}\, \rho \cdot \bar{u}^3 \cdot A = 1/2\ (1.02\ \mathrm{g/cm^3})\bar{u}^3(2 \times 10^8\ \mathrm{cm^2}) \qquad (41)$$

where ρ is the density of water 1.02 g/cm^3), $\bar{u}$ is mean current speed, and A is the cross-sectional area considered (2 x 10^8 cm^2). The mean kinetic energy for the affected area was thus computed to be 10.18 x 10^6 kcal/yr, while the area on the outskirts of the spoil bank influence had an estimated kinetic energy of 44.56 x 10^6 kcal/yr, for a difference of 34.38 x 10^6 kcal/yr. This is equivalent to about 58.45 x 10^6 kcal CE/yr assuming an energy quality factor of 1.7 (see Table 5). The mean velocity in the discharge canal is about 18.3 cm/sec and the cross section is approximately 1.81 x 10^6 cm^2, so that the plume's kinetic energy amounts to some 7.2 x 10^6 kcal (12.2 x 10^6 kcal CE/yr), which is about 21 percent of the energy loss to spoil bank erosion.

Unfortunately, no specific measurements were available to estimate eddy viscosities or small scale spatial gradients of energetically important estuarine substances. Nevertheless, a rough estimate was done to determine the possible loss of turbulent transport energies from the estuary due to effects of canal spoil banks. Vertical eddy viscosity, K_Z, was estimated as the mean vertical velocity, $\bar{u}_Z$, times mean depth, $\bar{Z}$ of affected area (Bowden, 1964; O'Brien, personal comm.),

$$\begin{aligned} K_Z &= (\bar{u}_Z) \cdot Z \\ &= (1\ \mathrm{cm/sec})(100\ \mathrm{cm}) = 10^2\ \mathrm{cm^2/sec} \end{aligned} \qquad (42)$$

Considering inorganic nitrogen as a representative, energetically important substance transported by diffusion, it was assumed that in 1 m depth of water, concentrations were vertically distributed by an exponential function with surface values at 30 mg/m^3 and bottom values at 35 mg/m^3. An equation describing the concentration of nitrogen as a function of depth would then be,

$$N = 30 + e^{bZ} \qquad (43)$$

where b is a constant coefficient. Knowing the boundary condition that $N = 35$ mg/m^3 at $Z = 1.0$ m, we can solve for $b = \ell n\ (5) = 1.6$. The second derivative of the nitrogen function (second term of Eq. (40) applied to Eq. (43)) can be computed very simply as,

$$\frac{\partial^2 N}{\partial Z^2} = b^2 e^{bZ} \qquad (44)$$

This is equal to 3.8×10^{-4} (mg/m^3)/cm^2 at Z = 25 cm, and therefore the entire second term of Eq. (1) is (irrespective of sign) 3.8×10^{-2} (mg/m^3)/sec. During an average day, very active uptake of nitrogen might take place for only 6 hrs. Assuming that a gram of nitrogen is equivalent to 66 kcal of productivity by stochiometry of the photosynthesis equation, and further assuming a mean depth of photosynthesis of .25 m, we compute the energy equivalent of this diffusive transport to be 0.68 kcal CE/m^2·day. If the percent reduction of turbulent energy resulting from canal spoil banks was assumed to be comparable to the spoil banks' effect on kinetic energy (i.e., 77% reduction), and if the affected area were to be taken as the inner plus outer bays (i.e., 1.77×10^6 m^2), the overall energy impact of canal spoil banks processes would be 100.4 x 10^6 kcal CE/yr. The net, total impact on advective and diffusive transport (subtracting the plume's kinetic energy) would be 146.7 x 10^6 kcal CE/yr.

Economic and Energetic Costs of Alternative Cooling Systems

Economic data and energy equivalents were examined for five technological schemes for handling cooling water in a closed-cycle system. Closed-circuit cooling alternatives have been proposed to minimize the power plant's impact on local ecosystems. The cooling systems themselves, however, would create some additional adverse effects on the environment by displacing natural ecosystems and by inhibiting productivity of surrounding marsh and terrestrial ecosystems with a continuous spray of salt.

Costs of Cooling Water Systems

The annual costs of five alternative cooling water methods are estimated in Table 24 for the Crystal River plant units 1-3 and for unit 3 alone. Calculations are taken from Gilbert Associates (1974) with the exception of costs for "modular spray" system on power plant unit #3. These latter figures were estimated by prorating the 3-unit system costs according to average ratios for the other four systems. In a summary analysis of these data by Florida Power Corp. (1974), the modular spray system was referred to as an open-cycle system; however, Gilbert Associates (1974) indicated that their designs and costs pertain to a closed-circuit system. The annual costs for all of these cooling systems were similar, with none deviating from the mean by more than 14%. The modular spray system would appear to be the least expensive at $16.1 million/yr for 3 power plant units and $8.7 million/yr for just unit 3. The multi-cell mechanical draft system is not far behind with annual costs of $9.2 and $17.9 million for unit 3 and units 1-3, respectively.

Table 24. Summary of cost estimates for cooling water management alternatives at Crystal River power plant.[a]

Cost Item	Power Plant Units Covered	Closed Circuit Alternatives ($\$10^6$)				
		Multi-cell Mech. Draft	Circular Mech. Draft	Natural Draft	Fan-Asstd. Nat. Draft	Modular Spray Units[c]
Capital Investment, Equipment and Installation[b]	#3	32.8	37.2	53.6	39.2	36.5
Present Worth 1978 U.S. Dollars	"	59.0	64.1	76.3	64.7	53.5
Annual Costs Capital Amortization Oper. and Maint.	"	9.2	10.1	12.4	10.2	8.7
Capital Investment, Eqpmt. and Installtn.	#1, 2, 3	61.5	63.7	83.9	72.4	64.1
Present Worth, 1978 U.S. Dollars	"	118.4	125.0	136.0	126.4	102.9
Annual Costs, Capital Amortization, Oper. and Maint.	"	17.9	18.9	21.2	19.4	16.1

[a] Table was adapted from Gilbert Associates (1974). Assumptions include: plant life = 30 yrs; load factor = 0.70 for Units 1-3, 0.75 for Unit 3; cost of capital = 11.25%; fixed charge rate = 17.3%; fuel = \$0.020/KWH; capacity = \$250/KW; 1% of yr hot enough to impose turbine penalty; once-through cooling system used as base cost.

Table 24. (Continued)

[b] Tower design factors are: T (range), T (wet bulb), T (approach),°F = 15.1, 79, 12, respectively, except Nat. Draft and Spray Modules for which T (approach) = 14, 16, respectively.

[c] Estimated on the basis of average cost ratios for Unit 3/Units 1-3 for other cooling alternatives.

These calculations assumed a 30 yr facility life, 11.25% interest on capital investment, 70% load factor for units 1-3 and 75% for unit 3 only. The costs of the once-through cooling system were used as a base level.

Ecological Effects of Cooling Systems

Effects of salt spray deposition on local terrestrial ecosystems were estimated for four alternative cooling water systems, and these are summarized in Table 25. Isopleths for salt deposition rate were obtained from Gilbert Associates (1974) and by Gutfreund and Urone (1972). Vegetation types in the areas of deposition were given by Dames and Moore (1974), and productivities of these ecosystems were taken from Table 6. Deposition rates were also compared to generalized predictions given by Roffman and Van Vleck (1974). The mechanical draft systems seemed to create the most salt spray, with the multi-cell producing smaller areas of deposition but higher rates and the circular system producing larger areas of deposition at lower rates. The fractional reductions in productivity for various deposition rates were estimated from data given in Fig. 30. Here the differential effects of various salt deposition rates (above background levels) on plant growth are indicated. Background levels of salt deposition were estimated from Yaalon and Lomas (1970) and Boyce (1954) for similar coastal regions. The total estimated impact on terrestrial plant production was relatively large, ranging from 0.10-3.27 x 10^9 kcal CE/yr. The salt spray effects of spray modular systems was assumed to be minimal (Gilbert Associates, 1974).

Table 25. Effects of salt spray deposition on terrestrial ecosystems for alternative cooling water management schemes for Crystal River power plant Units 1-3.

Salt Deposition Rate g/m^2·yr	Calculations Parameters	Footnote	Multi-Cell Mech. Draft	Circular Mech. Draft	Natural Draft Tower	Fan-Asstd. Natural Draft
44-88	Area affected, m^{2}x10^6	a	1.40			
	Productivity, kcal CE/m^2·yr	b	992			
	Fractional reduction	c	0.40			
	Total Prod. Lost, kcal CEx10^9/yr		0.56			
2	Area affected, m^{2}x10^6	a	5.99	2.43		
	Productivity, kcal CE/m^2·yr	b	1073	1073		
	Fractional reduction	c	0.20	0.20		
	Total Prod. Lost, kcal CEx10^9/yr		1.29	0.52		
9-11	Area affected, 10^{6}m^2	a	12.67	28.87	5.95	1.03
	Productivity, kcal CE/m^2·yr	b	1117	1117	992	992
	Fractional reduction	c	0.10	0.10	0.10	0.10
	Total Prod. Lost, kcal CEx10^9/yr		1.42	3.22	0.59	0.10
Total effect, kcal CEx10^9/yr			3.27	3.74	0.59	0.10

---

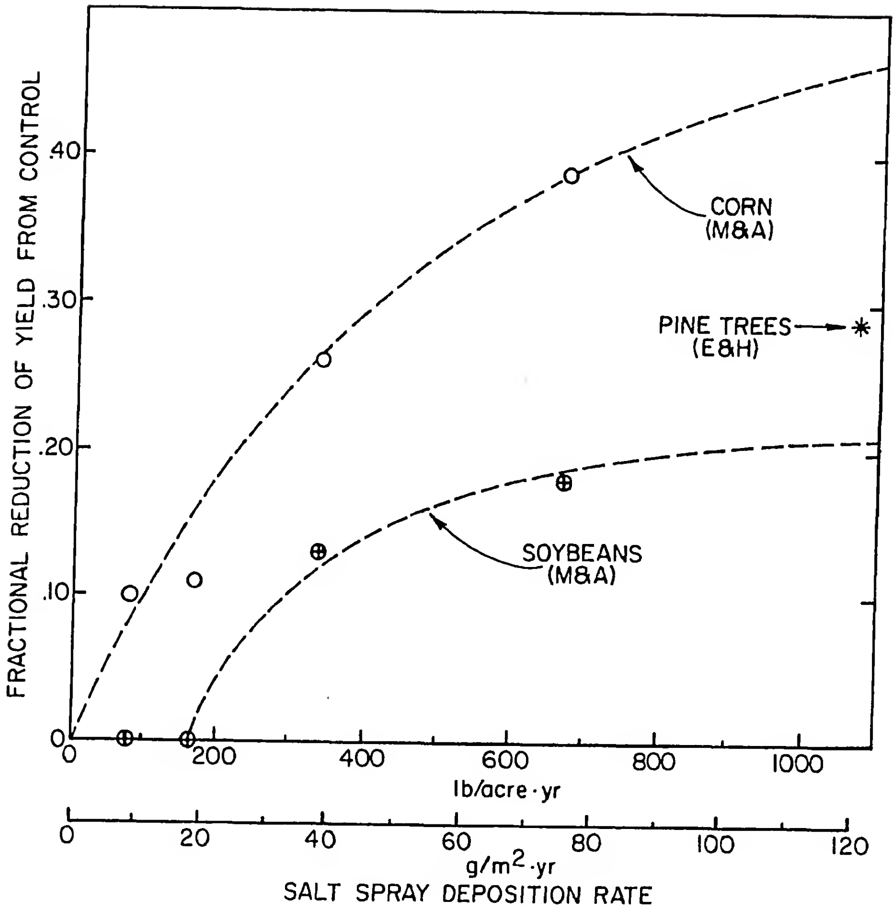
[a] Areas affected by given level of salt deposition for given cooling alternative are estimated from isopleths of salt spray deposits calculated by Gilbert Associates (1974). Areas are prorated for higher possible salinity of spray (34 ppt).

[b] Vegetation maps of Dames and Moore (1974) show which ecosystems are affected by which levels of deposition. Weighted mean productivity for entire area is calculated assuming that the productivities (kcal CE/m^2·yr) for community types affected are: saltmarsh = 1385; pine flatwoods = 595; planted pine = 600; mesic hammock = 830 (see Table 6).

Table 25. (Continued)

[c] Fractional reduction of production estimated from Mulchi and Armbruster (1975) data on corn for different salt loading rates (see Fig. 30).

Figure 30. Effects of salt spray deposition on growth of various kinds of vegetation. Data sources abbreviated: (M & A) = Mulchi and Armbruster (1975); (E & H) = Edwards and Holmes (1968). Curves were drawn by inspection.


FRACTIONAL REDUCTION OF YIELD FROM CONTROL
0
.10
.20
.30
.40
CORN
(M&A)
PINE TREES
(E&H)
SOYBEANS
(M&A)
0
200
400
600
800
1000
lb/acre · yr
0
20
40
60
80
100
120
g/m² · yr
SALT SPRAY DEPOSITION RATE

In Table 26 the energetic effects of displacing salt marsh ecosystems with cooling water systems was calculated. Plan drawings for each alternative facility were given by Gilbert Associates (1974), where the site for each structure was designated in the marsh between intake and discharge canals. Areas were computed from these drawings, and marsh productivity values were adapted from Young (1974a, b). The maximum effect of displacing salt marsh ecosystems by cooling facilities was equivalent to 1.04×10^9 kcal CE/yr for the modular spray system. Combining these on-site environmental effects of each alternative cooling water treatment scheme with the economic costs, the total energetic cost of each system was calculated. Thus, in Table 26 we see that the two economically cheapest plans (multi-cell mechanical and modular spray) have relatively large direct environmental effects associated with them.

Table 26. Comparative energetic costs of alternative cooling water management schemes: economic investments and terrestrial ecological impact for Crystal River power plant Units 1-3.

Energetic Cost kcal CEx10^9/yr	Multi-cell Mech. Draft	Circular Mech. Draft	Natural Draft Tower	Fan-Asstd. Mech. Draft	Modular Spray Units
1) Economic Investment,[a] Annual Costs	358.0	378.0	424.0	388.0	322.0
2) Ecosystems Displaced[b] by Construction	0.49	0.18	0.18	0.13	1.04
3) Stress of Salt Spray[c] Deposition	3.27	3.74	0.59	0.10	-----
Total	361.76	381.92	424.74	388.23	323.04

[a] Data from Table 23 converted to energy units assuming a general ratio for the U.S. economy equal to 20,000 kcal/(1973 U.S. $), from Kylstra (1974).

[b] Ecological productivity estimated by multiplying the mean annual salt marsh metabolism value in Table 25 times the areas used by each facility. Areas were measured from plan drawings given by Gilbert Associates (1974).

[c] Data taken from Table 24.

Field Measurements of Canal Ecosystems

Field measurements were made in the power plant canal ecosystems from 1973 to 1975. Data were collected in the present study for community photosynthesis and respiration, as well as for standing stocks and diversity of benthic animals and pelagic fish. Data from other researchers at Crystal River were also analyzed, adapted and integrated to develop a detailed description of the canal ecosystems. A generalized energy diagram is given in Fig. 31 to illustrate the major aggregated components of the intake and discharge canal ecosystems as they interact with adjacent bays and offshore systems and are interposed by the Crystal River power plant. The major categories of system components correspond directly to major divisions of field work reported herein. The model is evaluated with data reported at the end of this section.

Water Quality, Plankton and Metabolism of Canal Ecosystems

Total Community Metabolism. Detailed results of primary productivity and total respiration measurements in the canal ecosystems (as indicated from diurnal changes of dissolved oxygen between sequential stations) are reported in Table 27. Metabolism data given in Figs. 32-35 are generally for station pairs 2A-3 in the intake ecosystem and stations 5-6 in the discharge (see Fig. 5 for station locations). Throughout the study, salinity was relatively constant, with the mean diurnal values ranging from 25.4-29.4 o/oo. Annual temperature ranges during sampling dates were 14.0-31.5°C for the intake water and 20.2-37.4°C in the discharge canal, and these are representative of seasonal

Figure 31. Generalized energy diagram illustrating major aggregated components of intake and discharge canal ecosystems as they interact with adjacent bays and offshore systems and are interposed by the Crystal River power plant. The major categories of system components correspond to major divisions of field work reported in this study. Abbreviations are as follows:

S = Sunlight

T = TEMP = Temperature

PHOS = Phosphate

NITR = Nitrogen

ZOOP = Zooplankton

WDET = Seston or suspended detritus

PHYT = Phytoplankton

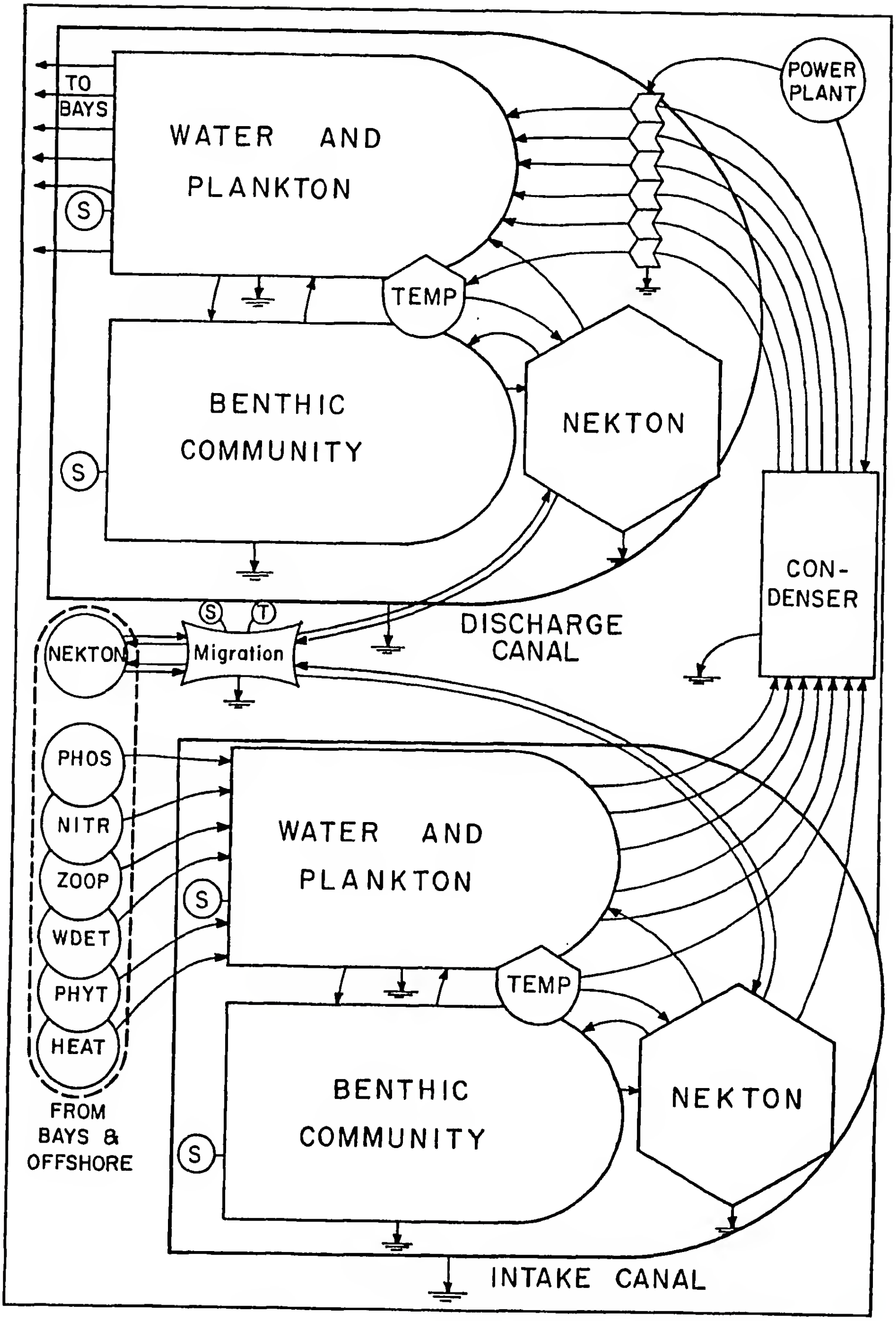

TO
BAYS
WATER AND
PLANKTON
S
POWER
PLANT
TEMP
BENTHIC
COMMUNITY
S
NEKTON
CON-
DENSER
DISCHARGE
CANAL
S
T
NEKTON
Migration
PHOS
NITR
ZOOP
WDET
PHYT
HEAT
FROM
BAYS &
OFFSHORE
WATER AND
PLANKTON
S
TEMP
BENTHIC
COMMUNITY
S
NEKTON
INTAKE CANAL

Table 27. Productivity and respiration data for total ecosystems in discharge and intake canals.

Date	Stas.	Sun-light kcal per $m^2 \cdot$day	Max. Diurnal Temp., °C	Mean Diurnal Salinity o/oo	Community Metabolism, g $O_2/m^2 \cdot day^a$				Percent Diffusion Correction
					P_N	R_N	P_G	P/R	
Late Spring									
1975:									
May 11-12	2A-3	--	29.5	26.2	4.28	3.88	8.16	1.05	5
	5-6	--	35.0	26.4	4.98	6.03	11.01	0.91	7
	2-2A	5308	29.2	26.2	4.50	4.16	8.66	1.04	2
	2A-3	--	29.4	26.2	2.98	4.62	7.60	0.83	4
	5-6	--	35.3	26.6	3.98	7.05	11.03	0.78	18
1974:									
Jun 26-27	3-4	6245	26.2	27.1	2.08	4.41	6.49	0.74	20
	5-6	--	33.4	27.2	1.84	5.96	7.80	0.65	16
Mean	2-2A	--	28.3	26.5	3.62±1.77	4.29±0.13	7.58±1.09	0.84±0.10	11
$\overline{x}$ ± SE	2A-3	5777	28.4	26.5	3.11±0.64	4.30±0.22	7.42±0.49	0.87±0.09	10
	5-6		34.6	26.7	2.91±0.93	6.35±0.36	9.95±1.08	0.78±0.08	14
Early Summer									
1974:									
Jul 1-2	2-3	4100	28.7	26.9	3.92	6.39	10.31	0.81	1
	5-6	--	35.4	27.0	3.49	4.98	8.47	0.85	21
Jul 10-11	2-3	5441	30.8	27.4	5.51	5.59	11.10	0.99	25
	5-6	--	35.3	26.3	4.13	5.58	9.71	0.87	32
Jul 17-18	2-3	5191	30.3	27.2	3.51	6.41	9.92	0.77	4
	5-6	--	36.3	27.4	5.37	5.96	11.33	0.95	16

Table 27. (Continued)

Date	Stas.	Sun-light kcal per $m^2 \cdot$day	Max. Diurnal Temp., °C	Mean Diurnal Salinity o/oo	Community Metabolism, g $O_2/m^2 \cdot day^a$				Percent Diffusion Correction
					P_N	R_N	P_G	P/R	
Mean	2-3	4911	29.9	27.2	4.31±0.61	6.13±0.27	10.44±0.35	0.86±0.07	10
$\bar{x}$ ± SE	5-6	--	35.7	26.9	4.33±0.55	5.51±0.29	9.84±0.83	0.89±0.03	23
Late Summer									
1974:									
Aug 12-13	2-2A	3714	30.7	26.3	2.16	7.47	9.63	0.64	6
	2A-3	--	30.7	26.3	1.95	9.07	11.02	0.61	5
	5-6	--	37.0	27.0	1.54	4.80	6.34	0.66	17
Aug 18-19	2-2A	6048	31.2	28.1	6.97	6.74	13.71	1.02	3
	2A-3	--	31.5	28.1	4.71	8.06	12.87	0.80	3
	5-6	--	37.4	28.2	3.71	6.48	10.19	0.79	15
Aug 25-26	2-2A	5796	31.1	27.8	6.72	5.05	11.77	1.17	6
	2A-3	--	31.2	27.8	7.69	6.56	14.25	1.09	3
	5-6	--	36.2	27.9	4.99	6.48	11.47	0.89	19
Sep 1-2	2-2A	5631	31.2	27.7	8.73	5.41	14.14	1.31	11
	2A-3	--	31.1	27.7	6.29	9.29	15.58	0.84	10
	5-6	--	37.0	27.9	4.35	8.48	12.83	0.76	7
Sep 10-11	2-2A	5256	30.0	28.5	9.81	3.56	13.37	1.88	10
	5-6	--	33.1	28.8	6.34	3.09	9.43	1.53	15
Mean[b]	2-2A	--	30.8	27.7	8.06±0.74	5.19±0.65	13.25±0.52	1.17±0.09	7
$\bar{x}$ ± SE	2A-3	5289	31.1	27.5	6.23±0.87	7.97±0.80	14.23±0.78	0.91±0.09	5
	5-6	--	36.1	28.0	4.85±0.56	6.13±1.13	10.98±0.75	0.81±0.04	15

Table 27. (Continued)

Date	Stas.	Sun-light kcal per $m^2 \cdot day$	Max. Diurnal Temp., °C	Mean Diurnal Salinity o/oo	Community Metabolism, g $O_2/m^2 \cdot day^a$				Percent Diffusion Correction
					P_N	R_N	P_G	P/R	
Fall									
1974:									
Nov 28-29	2-2A	--	16.5	28.2	2.28	2.31	4.59	0.99	8
	2A-3	--	16.7	28.2	2.37	3.17	5.54	0.87	8
	5-6	--	24.5	28.4	4.06	1.40	5.46	1.95	37
Nov 29-30	2-2A	--	16.0	28.0	2.00	3.53	5.53	0.78	13
	2A-3	--	16.2	28.0	2.20	2.67	4.87	0.91	10
	5-6	--	22.2	28.1	2.29	2.10	4.39	1.05	40
Dec 1-2	2A-3	--	15.8	29.3	2.42	4.15	6.57	0.79	6
	5-6	--	22.4	29.4	3.14	2.47	5.61	1.14	36
Mean	2-2A	--	16.3	28.1	2.14±0.14	2.92±0.61	5.06±0.47	0.89±0.11	11
x ± SE	2A-3	--	16.2	28.5	2.33±0.07	3.33±0.47	5.66±0.50	0.86±0.04	8
	5-6	--	23.0	28.6	3.16±0.51	1.99±0.31	5.15±0.38	1.38±0.29	38
Winter									
1975:									
Feb 14-15	2-2A	3395	18.8	25.7	1.56	2.82	4.38	0.78	0
	2A-3	--	19.0	25.7	1.40	2.63	4.03	0.78	3
	5-6	--	24.5	25.8	3.53	3.97	7.50	0.94	32
Feb 15-16	2-2A	2964	19.4	25.9	2.73	2.60	5.33	1.03	4
	2A-3	--	19.9	25.9	1.43	4.39	5.82	0.66	3
	5-6	--	23.5	25.9	2.77	4.74	7.51	0.79	28
Feb 16-17	2A-3	2861	21.1	25.4	0.51	2.12	2.63	0.62	8
	5-6	--	25.0	25.6	2.71	4.41	7.12	0.81	33

Table 27. (Continued)

Date	Stas.	Sun-light kcal per $m^2 \cdot$day	Max. Diurnal Temp., °C	Mean Diurnal Salinity o/oo	Community Metabolism, g $O_2/m^2 \cdot day$[a]				Percent Diffusion Correction
					P_N	R_N	P_G	P/R	
Mean $\bar{x}$ ± SE	2-2A	--	19.1	25.8	2.15±0.59	2.71±0.11	4.86±0.48	0.91±0.13	2
	2A-3	3073	20.0	25.7	1.11±0.30	3.05±0.69	4.16±0.93	0.69±0.05	5
	5-6	--	24.3	25.8	3.00±0.26	4.37±0.23	7.38±0.13	0.85±0.05	31
Annual Mean[c] $\bar{x}$ ± SE	2-2A	--	23.5	27.0	3.54±0.96	3.87±0.68	6.26±0.75	0.91±0.04	8±2
	2A-3	--	23.8	27.0	2.96±0.87	4.43±0.91	7.39±1.98	0.83±0.05	8±1
	5-6	--	29.5	27.1	3.42±0.4	4.63±0.98	8.22±1.22	0.97±0.14	26.6

[a] Abbreviations for metabolic functions: P_N = net photosynthesis; R_N = night respiration; P_G = gross photosynthesis, estimated as $P_N + R_N$; P/R = ratio of $P_G/(R_N/1 - f)$ where f is daylight fraction of diel period.

[b] Data for Sept. 10-11 are not included in mean P/R ratio calculation. Data for Aug. 12-13 are not included in means because of highly reduced solar radiation leading to unusually low photosynthesis.

[c] Annual means are average of four seasonal means, where summer season is considered in two halves.

Figure 32. Daytime net productivity and night respiration of total ecosystems in canals at Crystal River power plant for 1974-75. Net productivity is plotted on upper (positive) plane. Respiration is plotted on lower (negative) plane. Circles with dashed line indicate intake canal ecosystem, and squares with solid line represent discharge canal.

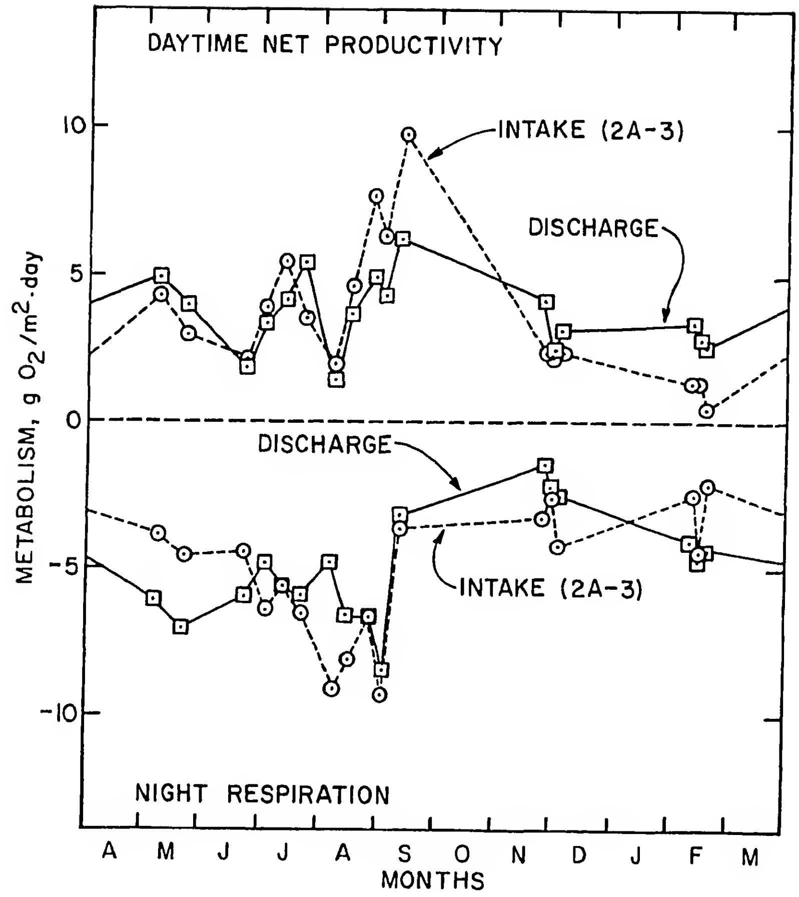

DAYTIME NET PRODUCTIVITY
INTAKE (2A-3)
DISCHARGE
DISCHARGE
INTAKE (2A-3)
NIGHT RESPIRATION
METABOLISM, g O_2/m^2.day
10
5
0
-5
-10
A
M
J
J
A
S
O
N
D
J
F
M
MONTHS

Figure 33. Seasonal trends for net productivity and respiration of canal ecosystems at Crystal River power plant for 1974 and 1975. Five seasons are defined as late spring, early summer, late summer, fall and winter. Points represent mean values ($\overline{X}$) with vertical bars indicating one standard error (S.E.) above and below the mean and integers above bars indicating number of samples per mean (n).

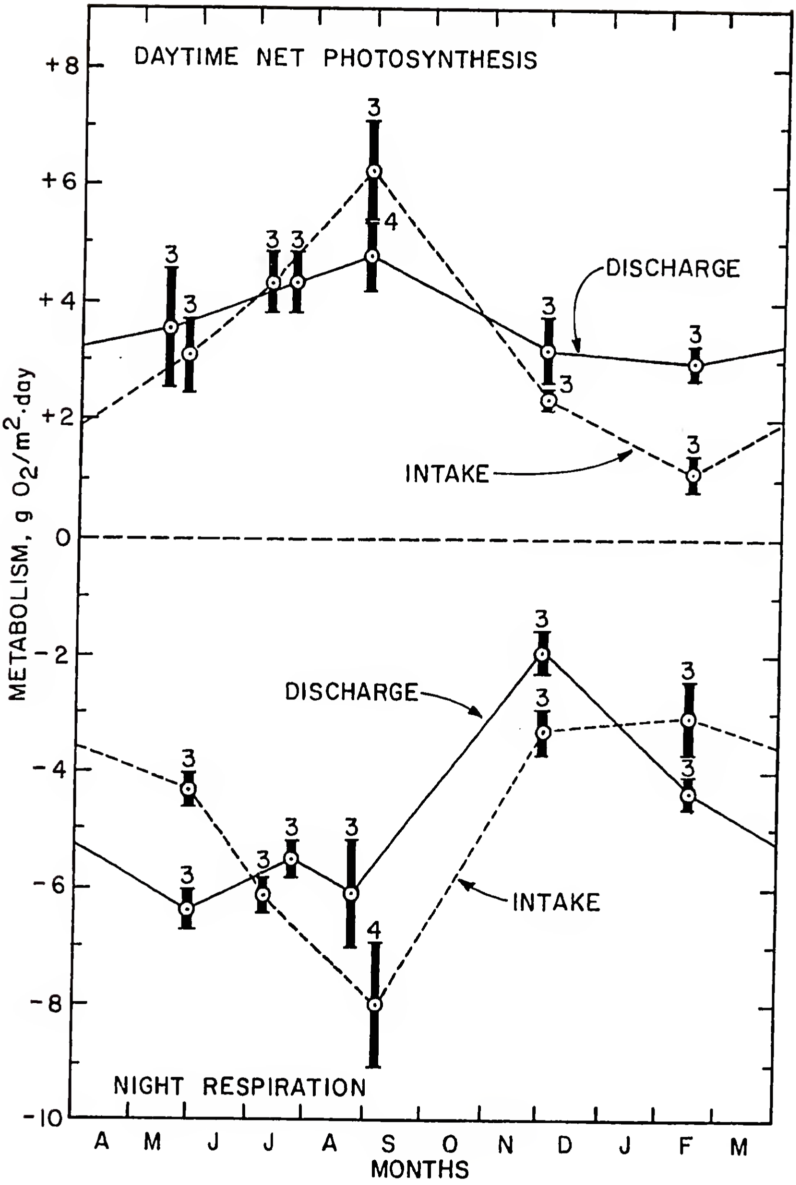

DAYTIME NET PHOTOSYNTHESIS
DISCHARGE
INTAKE
NIGHT RESPIRATION
DISCHARGE
INTAKE
METABOLISM, g $O_2/m^2\cdot day$
+8
+6
+4
+2
0
-2
-4
-6
-8
-10
3
4
A M J J A S O N D J F M
MONTHS

Figure 34. Seasonal trends for gross productivity of total ecosystems in canals at Crystal River power plant for 1974 and 1975. Gross productivity is approximated as net productivity plus night respiration. Points represent $\overline{X}$, vertical bars indicate ±1 S.E. and values above bars indicate number of samples per mean, n.

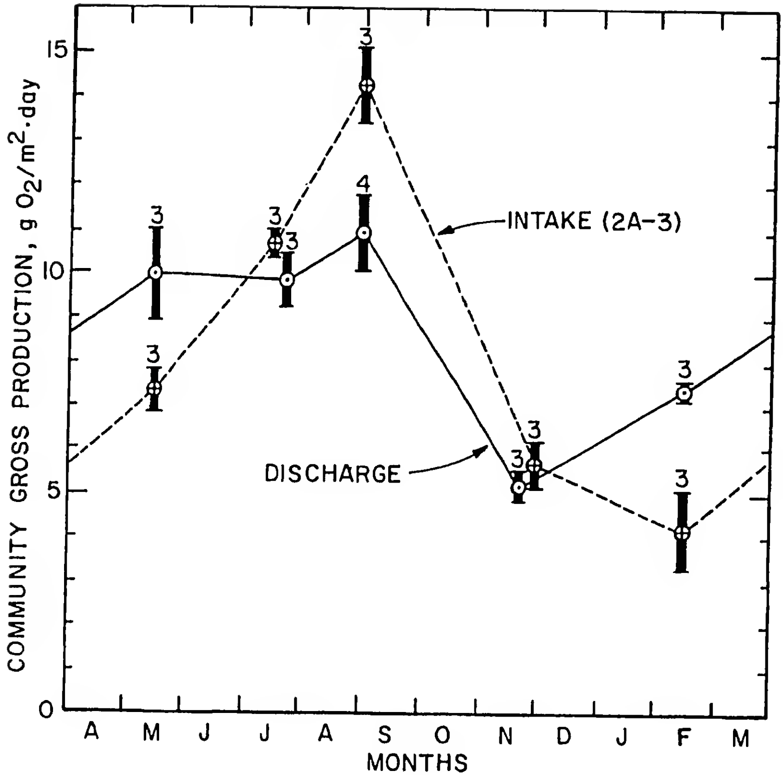
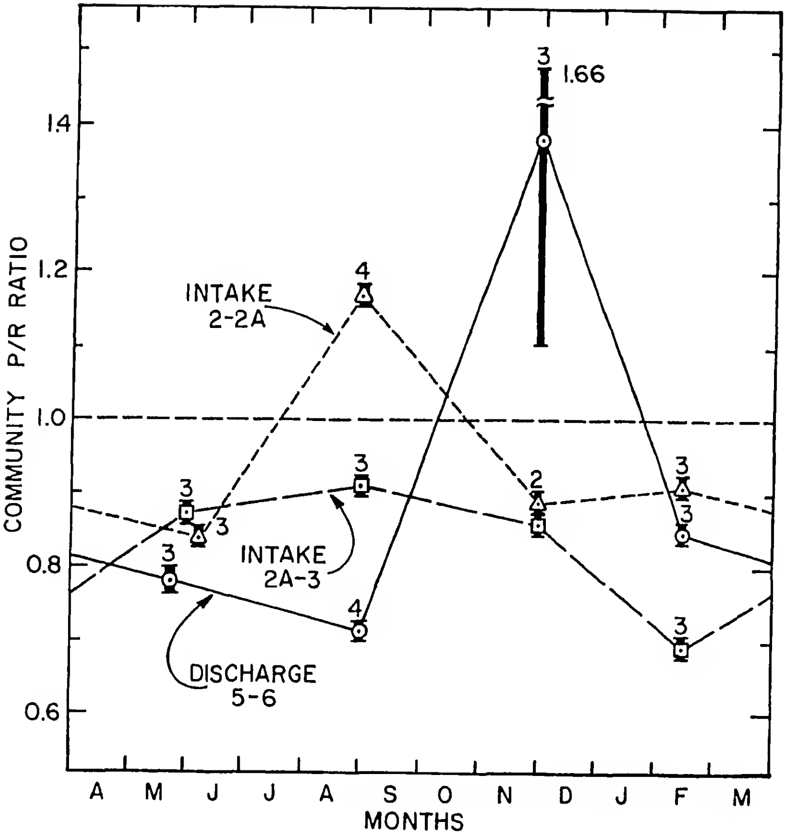

COMMUNITY GROSS PRODUCTION, g $O_2/m^2 \cdot day$
15
10
5
0
A
M
J
J
A
S
O
N
D
J
F
M
MONTHS
INTAKE (2A-3)
DISCHARGE
3
3
3
3
3
4
3
3
3
3
3

Figure 35. Seasonal trends for P/R ratio of total ecosystems in canals at Crystal River power plant for 1974 and 1975. P/R is ratio of gross productivity to 24·hr respiration. Points represent $\overline{X}$, vertical bars indicate ± 1 S.E., and numbers indicate n.


COMMUNITY P/R RATIO
1.4
1.2
1.0
0.8
0.6
MONTHS
A
M
J
J
A
S
O
N
D
J
F
M
INTAKE 2-2A
INTAKE 2A-3
DISCHARGE 5-6
1.66
3
4
3
3
3
4
3
2
3
3
3
3

trends for the region (see Fig. 79g). Solar insolation measurements ranged from 2861 $\mathrm{kcal/m^2 \cdot day}$ in February to 6245 $\mathrm{kcal/m^2 \cdot day}$ in June, with a mean of four seasonal averages equal to 4300.

Metabolism data given in Table 27 are plotted in several ways to illustrate seasonal patterns. Results from each sampling study are shown in Fig. 32, with daytime net productivity given in the positive (upper) half of the figure and night respiration presented in the negative (lower) half. In general both photosynthesis and respiration appear to be higher in the intake canal during the summer and lower in the colder months. Respiration (R) and photosynthesis (P) follow the same general trends with P leading R in the spring but P lagging slightly behind R in the late summer.

In Fig. 33 the time series data are aggregated into five general metabolic seasons: late spring; early summer; late summer; fall; and winter. Summer was split into early and late halves because of important climatic differences between these periods. July was characterized by moderately high sunlight and temperate while August and September had similar (though slightly higher) incident solar radiation but substantially hotter water temperatures. Net photosynthesis was significantly greater in the intake canal ecosystem than in the discharge canal during the late summer, but significantly lower than the discharge in fall and winter (95% confidence with paired t-test, pairing simultaneous measurements in discharge and intake canals).* Similarly, community respiration for the intake canal was significantly greater than for the discharge during August and Sepbember, but less than the discharge canal ecosystem during winter conditions. Both R and P measured for the intake canal community are significantly different from season to season throughout the year except for respiration between fall and winter. Seasonal trends are less marked or non-existent in the discharge canal. There are no significant seasonal differences (between adjacent seasons) for net production in the discharge canal community throughout the year, and the only significant seasonal trends for respiration occur around fall and winter. For the winter net production is greater in the discharge canal but respiration is less. During the rest of the year any trend in P is mirrored by a similar pattern for R.

---

* This criterion for significant differences between mean values will be used throughout this study unless otherwise indicated.

In Fig. 34 the values for daytime net productivity are added to night respiration to give an index of gross primary productivity. For this to be an accurate measure of gross production, night respiration would have to be equal to daytime respiration. In this figure a clear trend is evident, with gross production significantly greater in the intake canal during the late summer (August and September), but statistically greater in the discharge canal ecosystem during the spring and winter. Within the context of this pattern the transition seasons (fall and early summer) experienced similar levels of gross primary productivity in both canals. Whereas net productivity was higher in the discharge canal during the fall, gross productivity was the same in both canals for this season.

The ratio of gross productivity to 24 hr respiration (assumed to be the hourly rates of night respiration taken over 24 hours) was used as an index of the relative balance between autotrophy and heterotrophy in these ecosystems. This P/R ratio is plotted in Fig. 35 for data from three station pairs (2-2A and 2A-3 in the intake, and 5-6 in the discharge). In general all stations exhibited predominant heterotrophic conditions with (P/R) < 1.0. However, the P/R ratio of the outer part of the intake canal (sta. 2-2A) was significantly higher than that of the inner part of the canal (sta. 2A-3) except during spring when there was no difference. The discharge canal ecosystem had significantly lower P/R ratios in the warmer spring and summer months, but had higher ratios in the colder fall and winter months.

Plankton Metabolism. Results from measurement of productivity and respiration of plankton (as indicated by DO changes in light and dark bottles) are given in Table 28. Also presented are percentages of total community gross productivity comprised by phytoplankton in the canal ecosystems. The plankton portion of total production was greater in the intake canal than in the discharge, and the annual mean value was significantly higher in the intake (34%) than in the discharge (20%). Proportions of plankton productivity to total productivity were statistically different only in the spring and summer months.

Mean values of an index of gross primary productivity of phytoplankton are given in Fig. 36 ($P_N + R_N$) for the five metabolic seasons defined earlier. Plankton productivity was greater in the intake canal ecosystem than in the discharge canal throughout the year (except winter when there was no difference), however, those differences were significant only in the summer. The intake canal plankton exhibited marked seasonal patterns with productivity in the warmer months significantly greater than in colder months. However, in the discharge canal ecosystem there was a conspicuous absence of seasonablity, and seasonal mean productivities are significantly different only between winter and spring. The variance of gross productivity over an annual

Table 28. Productivity and respiration of plankton in discharge (D) and intake (I) canal ecosystems measured by light-dark bottles.

Date	Intake (I) or Discharge (D) Canal	Plankton Metabolism,[a] g $O_2/m^2 \cdot day$				% Total P_G from Plankton
		P_N	R_T	P_G	P/R	
Late Spring						
1975:						
May 11-12	I	2.40	2.21	3.50	1.58	43
	D	0.02	4.41	2.23	0.51	20
	I	1.75	3.45	3.48	1.01	43
	D	1.01	4.86	3.44	0.71	31
1974:						
Jun 26-27	I	0	3.52	1.76	0.50	27
	D	-0.17	3.04	1.35	0.44	17
Mean, $\bar{x}$ ± SE	I	1.38±0.72	3.06±0.43	2.91±0.58	1.03±0.31	38±5
	D	0.29±0.37	4.10±0.55	2.34±0.61	0.55±0.08	23±4
Early Summer						
1974:						
Jul 1-2	I	1.93	5.09	4.48	0.88	43
	D	0.50	2.94	1.98	0.67	23
Jul 10-11	I	1.29	2.99	2.79	0.93	25
	D	0.06	2.76	1.44	0.52	13
Jul 17-18	I	0.58	3.07	2.12	0.69	21
	D	-0.76	2.52	0.50	0.20	4
Mean, $\bar{x}$ ± SE	I	1.27±0.39	3.72±0.69	3.13±0.70	0.83±0.07	30±7
	D	-0.07±0.37	2.74±0.12	1.31±0.43	0.46±0.14	13±6
Late Summer						
1974:						
Aug 12-13	I	0.63	4.09	2.68	0.66	26
	D	-2.57	5.67	0.17	0.03	3
Aug 18-19	I	0.42	4.76	2.80	0.59	21
	D	-0.68	3.59	1.11	0.31	11
Aug 25-26	I	1.03	5.85	3.96	0.68	31
	D	-0.48	3.60	1.32	0.37	12
Sep 1-2	I	8.31	9.17	16.89	1.84	108
	D	-2.66	6.20	0.44	0.07	1
Sep 10-11	I	4.35	5.85	7.28	1.24	54
	D	7.04	5.00	9.54	1.91	101
Mean,[b] $\bar{x}$ ± SE		2.60±1.91	5.94±0.87	6.58±3.45	0.96±0.30	47±21
		-1.60±0.59	4.81±0.53	0.76±0.27	0.20±0.09	7±3

Table 28. (Continued)

Date	Intake (I) or Discharge (D) Canal	Plankton Metabolism,[a] g $O_2/m^2 \cdot$day				% Total P_G from Plankton[d]
		P_N	R_T	P_G	P/R	
Fall						
1974:						
Nov 28-29	I	0.32	1.44	1.04	0.72	21
	D	0.36	0.78	0.75	0.96	14
Nov 29-30	I	0.47	0.39	0.67	1.72	13
	D	0.26	0.59	0.56	0.95	13
Dec 1-2	I	0.22	0.98	0.71	0.72	11
	D	-0.45	2.57	0.84	0.33	15
Mean, $\bar{x}$ ± SE	I	0.34±0.07	0.94±0.30	0.81±0.12	1.05±0.33	15±3
	D	0.06±0.26	1.31±0.63	0.72±0.08	0.75±0.21	14±1
Winter						
1975:						
Feb 14-15	I	0.60	1.11	1.16	1.05	28
	D	0.74	1.44	1.46	1.01	19
Feb 15-16	I	0.43	0.65	0.76	1.17	14
	D	0.35	1.17	0.94	0.80	13
Feb 16-17	I	0.56	1.43	1.28	0.90	49
	D	-0.07	2.57	1.21	0.47	36
Mean, $\bar{x}$ ± SE	I	0.53±0.05	1.06±0.23	1.07±0.16	1.04±0.08	30±10
	D	0.34±0.23	1.73±0.43	1.20±0.15	0.76±0.16	23±7
Annual Mean[c] $\bar{x}$ SE	I	1.05±0.37	2.48±0.93	2.41±0.94	1.00±0.04	20±6
	D	-0.04±0.27	2.72±0.71	1.32±0.35	0.60±0.10	18±3

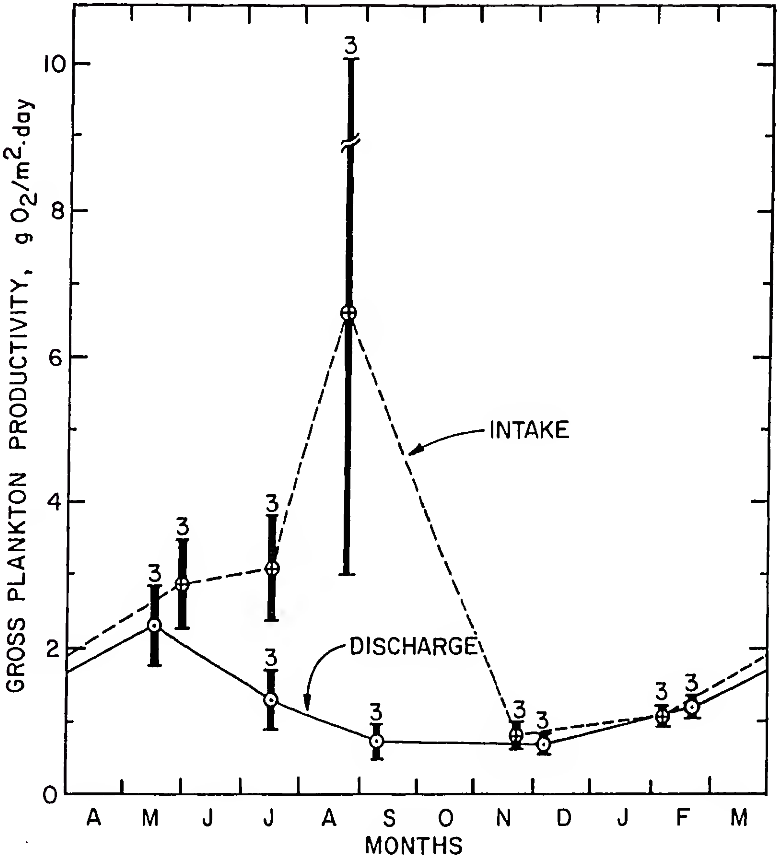
[a] P_N is net photosynthesis; R_T is 24-hour dark respiration; P_G is gross photosynthesis estimated as P_N plus f x R_T, where f is daylight fraction of diel period; P/R is ratio of P_G to R_T.

[b] Data for Sep 10-11 not included in totals. See footnote (b), Table 27.

[c] Annual means are average of four seasonal means, where summer season is considered in two halves.

[d] Percent of gross productivity of total community (see Table 27) contributed by plankton.

Figure 36. Seasonal trends for gross productivity of the plankton communities (as measured by light-dark O_2 bottles) in canals at Crystal River power plant for 1974 and 1975. Points represent $\overline{X}$, vertical bars indicate ± 1 S.E. and numbers indicate n.

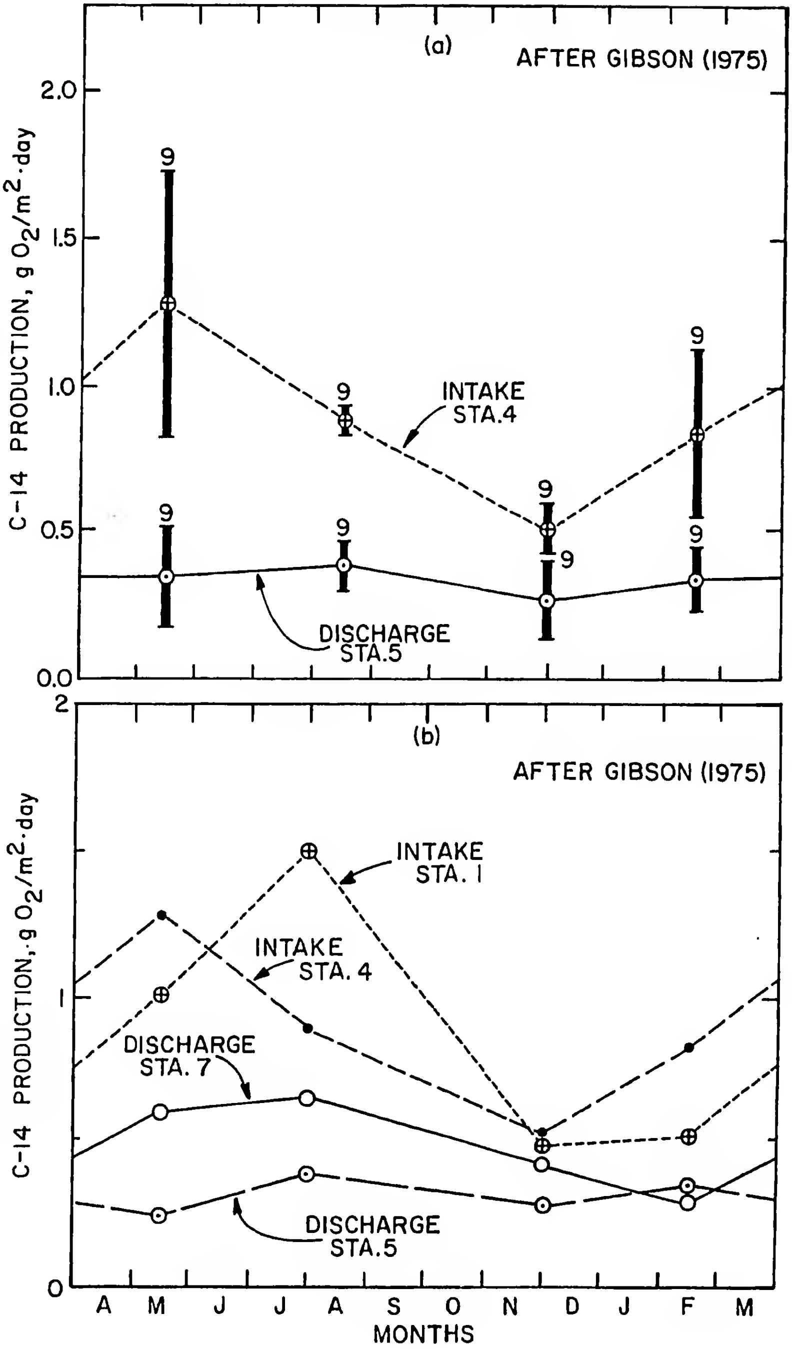

GROSS PLANKTON PRODUCTIVITY, g $O_2/m^2\cdot day$
0
2
4
6
8
10
3
3
3
3
3
3
3
3
3
3
INTAKE
DISCHARGE
A
M
J
J
A
S
O
N
D
J
F
M
MONTHS

cycle is significantly higher (F-test at 95% confidence) in the intake canal than in the discharge.

Carbon-14 productivity measured for the canal ecosystems by Gibson (1975) is given in Fig. 37. Seasonal mean values exhibited a similar pattern as did oxygen productivity measurements (Fig. 37a), with significantly greater amplitude of annual cycling in the intake canal and no statistical difference between seasons in the discharge canal. The Carbon-14 data exhibited greater variability from month-to-month than from season-to-season, whereas the difference between sequential seasonal means was significantly greater (95% confidence, Student's t-test) than the difference between sequential monthly measurements of oxygen productivity for the intake canal. The light-dark bottle oxygen measurements of plankton gross productivity were generally 1.5 to 6.5 times greater than the Carbon-14 measurements.

In Fig. 37b the seasonal means of Carbon-14 productivity (Gibson, 1975) are given for two intake canal stations (1 and 4) and two discharge canal stations (5 and 7) to investigate canal modifications of plankton metabolism. In the intake canal productivity is decreased by 60% in the summer as water flows from the outer entrance to the power plant, but during the winter and spring the reverse is true with metabolism increases of 70% and 25%, respectively, as water moved from station 1 to station 4. Plankton productivity was depressed in the discharge canal compared to the intake throughout the year; however, as effluent water traverse down the discharge canal from sta. 5 sta. 7 productivity recovered back to its original level during all seasons except winter when there was no change. This production increase down the discharge canal ranged from 30% to 130%. Seasonal means

Figure 37. Seasonal trends of carbon-14 productivity for plankton communities in canals at Crystal River power plant for 1974. Data is adapted from Gibson (1975). Points represent $\overline{X}$, vertical bars indicate ± 1 S.E. and numbers indicate n. (a) Seasonal means with variability for intake station 4 and discharge station 5. (b) Seasonal means for two intake stations (1 and 4) and two discharge stations (5 and 7). See Fig. 5 for station locations.


(a)
AFTER GIBSON (1975)
C-14 PRODUCTION, g $O_2/m^2 \cdot day$
2.0
1.5
1.0
0.5
0.0
9
INTAKE STA.4
DISCHARGE STA.5
(b)
AFTER GIBSON (1975)
2
1
0
INTAKE STA. 1
INTAKE STA. 4
DISCHARGE STA. 7
DISCHARGE STA.5
A M J J A S O N D J F M
MONTHS

of the ratio of plankton gross productivity to 24-hour respiration (P/R) are given in Fig. 38. The intake canal plankton community was autotrophic with P/R ratio 1.0 in all but the early summer months, whereas the discharge canal plankton was heterotrophic ($P/R<1.0$) throughout the year with lowest ratios (0.20) in the late summer.

Extinction of Solar Radiation. Given in Table 29 are data on depth of secchi disk disappearance and extinction coefficient for sunlight in canal ecosystem waters at Crystal River. Extinction coefficients (k) were estimated for submarine photometer measurements on six occasions in February and November. These measurements of k were regressed against secchi disk (d) readings done simultaneously, and a significant relationship (comparing variance of slope with the slope itself, according to Snedeker and Cochran, 1967) was indicated. The observed function was, $k = 1.02/d$ with $r^2 = 0.90$, and this expression was used to convert all other secchi disk readings to equivalent extinction coefficients. Light transparency data from Table 29 is summarized in Fig. 39. In all months measured, water was more transparent in the intake canal than in the discharge canal, and this difference was statistically significant during August and September. The difference in extinction coefficient between canals exhibits a seasonal trend, being generally greater during the warmer months.

There are two major sources of water entering the canal, one brackish nearshore water and the other saline Gulf water. Presumably, the above observed difference in extinction coefficient between canals (Δk) is a function of source water characteristics. The degree of vertical stratification in the intake canal is indicated by the vertical salinity gradient (ΔS). If stratification is directly related to the

Figure 38. Seasonal trends of P/R ratios of plankton metabolism in canals at Crystal River power plant for 1974 and 1975. Points represent $\overline{X}$, vertical bars indicate ± 1 S.E. and numbers indicate n.

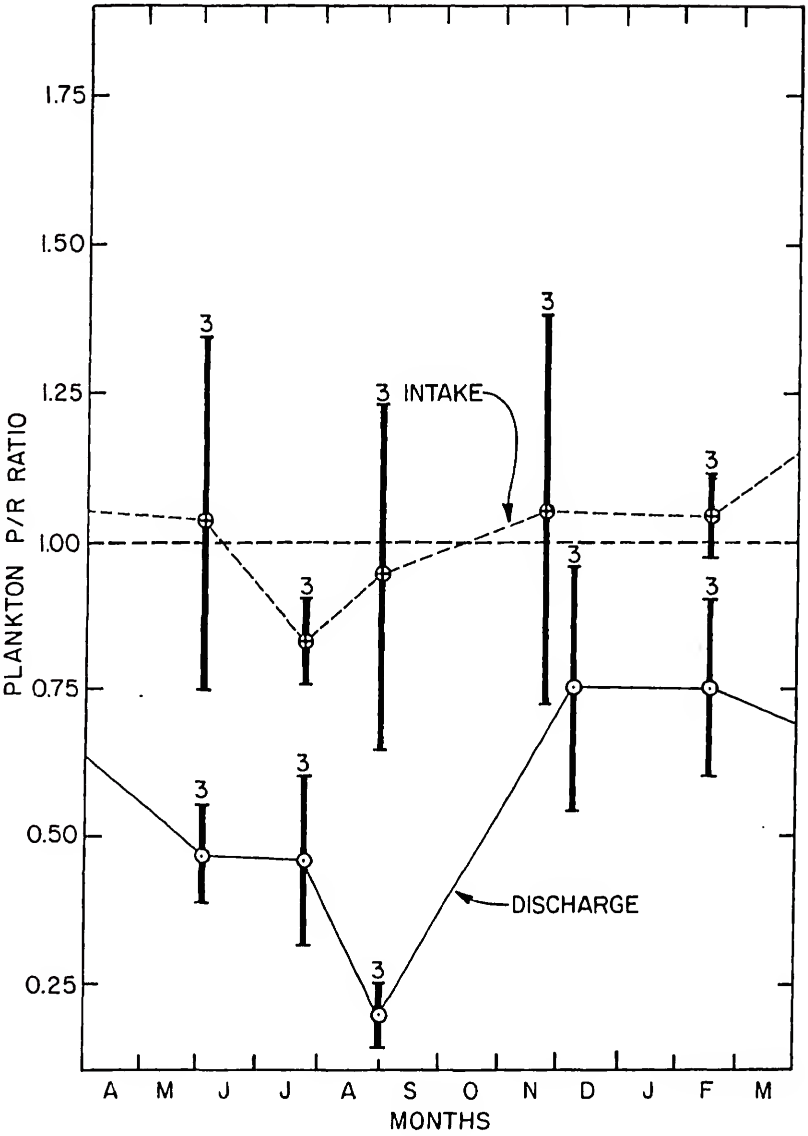

PLANKTON P/R RATIO
1.75
1.50
1.25
1.00
0.75
0.50
0.25
INTAKE
DISCHARGE
3
A
M
J
J
A
S
O
N
D
J
F
M
MONTHS

Table 29. Light extinction in waters of intake and discharge canals at Crystal River power plant.

Date			Secchi Disk, m		Extinction Coeff., k^a		Diff. in k Between Canals
Mo.	Yr.	hr.	Intake	Discharge	Intake	Discharge	
May	1975	1130	3.00	2.80	0.34	0.36	+0.02
		1500	2.50	2.40	0.41	0.43	+0.02
May[b]	1972	--	--	--	0.58	0.61	+0.03
		--	--	--	0.56	0.59	+0.03
				$\bar{x}$ ± SE	0.47±0.06	0.50±0.06	+0.03
June[c]	1971	0930	1.10	1.00	0.93	1.02	+0.09
		1500	1.50	0.90	0.68	1.13	+0.45
				$\bar{x}$ ± SE	0.81±0.13	1.08±0.06	+0.27
July[b]	1972	--	--	--	0.79	1.44	--
July[d]	1973	--	--	0.90	--	1.13	--
		--	--	1.20	--	0.85	--
				$\bar{x}$ ± SE	0.79±0	1.14±0.18	+0.35
Aug	1974	1200	1.55	1.00	0.66	1.02	+0.36
			1.45	1.05	0.70	0.97	+0.27
		1300	2.20	1.65	0.46	0.62	+0.16
			2.05	1.55	0.51	0.66	+0.15
		1500	1.65	1.20	0.62	0.97	+0.35
			1.45	1.00	0.70	0.85	+0.15
Aug[b]	1972	--	--	--	1.00	1.08	+0.08
				$\bar{x}$ ± SE	0.66±0.07	0.89±0.07	+0.22

Table 29. (Continued)

Date			Secchi Disk, m		Extinction Coeff., k[a]		Diff. in k Between Canals
Mo.	Yr.	hr.	Intake	Discharge	Intake	Discharge	
Sept	1974	0800	2.20	1.70	0.46	0.60	+0.14
			2.10	1.85	0.49	0.55	+0.06
		1200	1.70	0.55	0.60	1.85	+1.25
			1.80	0.90	0.57	1.13	+0.56
		1530	1.90	1.25	0.54	0.82	+0.28
			1.80	1.20	0.57	0.85	+0.28
Sept[d]	1973	--	2.10	1.60	0.49	0.64	+0.15
			2.35	1.55	0.43	0.66	+0.23
				$\bar{x}$ ± SE	0.52±0.02	0.89±0.15	+0.37
Nov	1975	1330	--	1.35	--	0.76	--
			--	1.45	--	0.70	--
		1330	1.80	1.80	0.57	0.57	0
Nov[d]	1973		1.90	--	0.54	--	--
			2.10	--	0.49	--	--
			1.70	--	0.60	--	--
				$\bar{x}$ ± SE	0.55±0.02	0.68±0.06	0
Feb	1975	1200	2.65	1.90	0.38	0.54	+0.16
			2.05	2.00	0.50	0.51	+0.01
		1300	2.20	1.70	0.46	0.62	+0.16
			2.05	1.85	0.51	0.66	+0.15
			2.00	2.40	0.51	0.43	+0.08
		1400	2.50	2.20	0.41	0.46	+0.05
			3.00	2.20	0.34	0.46	+0.12

Table 29. (Continued)

Date			Secchi Disk, m		Extinction Coeff., k[a]		Diff. in k Between Canals
Mo.	Yr.	hr.	Intake	Discharge	Intake	Discharge	
				$\bar{x} \pm$ SE	0.44±0.03	0.53±0.03	+0.10
Apr[c]	1971	1030	1.50	1.00	0.68	1.02	+0.34
		1430	1.00	1.00	1.02	1.02	0
		1730	1.30	1.00	0.78	1.02	+0.24
				$\bar{x} \pm$ SE	0.83±0.10	1.02±0	+0.19

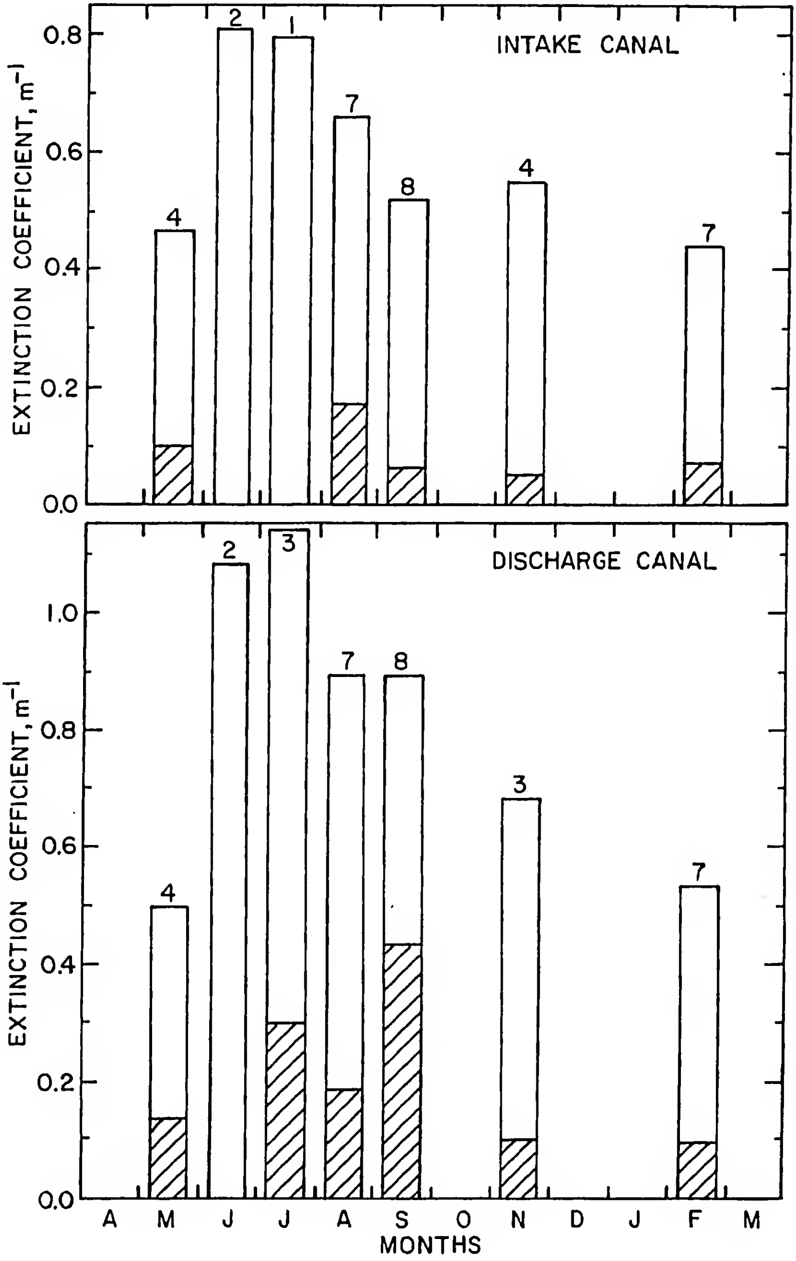
[a] Extinction coefficient (k) correlated to Secchi disk (d), where k = 1.02/d.

[b] Unpublished data collected by D. Young.

[c] Data from publication by Fox and Moyer (1973).

[d] Unpublished data collected by H. McKellar.

Figure 39. Extinction of solar radiation by water in canals at Crystal River power plant, 1972-1975. Extinction coefficients are inferred from subphotometer measurements as shown in Fig. and from Secchi disc readings. Four data points are taken from Fox and Moyer (1973). Height of bars represents mean value for given month; height of cross-hatched area indicates one standard error; and numbers at top of bars indicate number of measurements.


INTAKE CANAL
EXTINCTION COEFFICIENT, m⁻¹
0.0
0.2
0.4
0.6
0.8
4
2
1
7
8
4
7
DISCHARGE CANAL
EXTINCTION COEFFICIENT, m⁻¹
0.0
0.2
0.4
0.6
0.8
1.0
4
2
3
7
8
3
7
A
M
J
J
A
S
O
N
D
J
F
M
MONTHS

extent of brackish water sources (Klausewitz et al., 1974), then a relationship between ΔS and Δk might indicate turbidity characteristics of source water. A significant regression between these two parameters was obtained, where

$$(\Delta S) = 0.5 \log (\Delta k) \quad .$$

Data for this relationship are given in Fig. 40.

Assembled Data on Plankton Stocks and Water Quality. Chlorophyll-a concentrations for live phytoplankton (corrected for phaeophytin-a) in canal ecosystems were given in Fig. 41. The data are highly variable, with no distinct seasonal trends except that mid-summer and early spring blooms seem to have occurred, with autumn being the season of least abundance. Chlorophyll-a may be an index of phytoplankton standing stocks, and total organic carbon (Fig. 42) may be a measure for standing stocks of all seston including phytoplnakton, zooplankton and detritus. In Fig. 42 the pattern (or lack thereof) is similar to that of Fig. 41 for chlorophyll-a. However, there was considerably less variability. Carbon data corroborated the late summer and early spring blooms suggested by the data on chlorophyll-a. There was no significant difference between total sestonic organics in the two canal ecosystems. Seasonal patterns of the ratio (assimilation efficiency) mgC assimilated per hour per mg Chl-a stocks were less variable than observed for chlorophyll-a data.

Analyses from Gibson (1975) are given for total inorganic nitrogen (Fig. 43), nitrate, nitrite and ammonia, and phosphate (Fig. 44). Inorganic nitrogen was generally higher in the discharge canal than in the intake canal and differences were statistically significant during

Figure 40. Graph of vertical salinity gradient (ΔS) versus difference in extinction coefficient (Δk) between the intake and discharge canals at Crystal River power plant for 1974 and 1975.

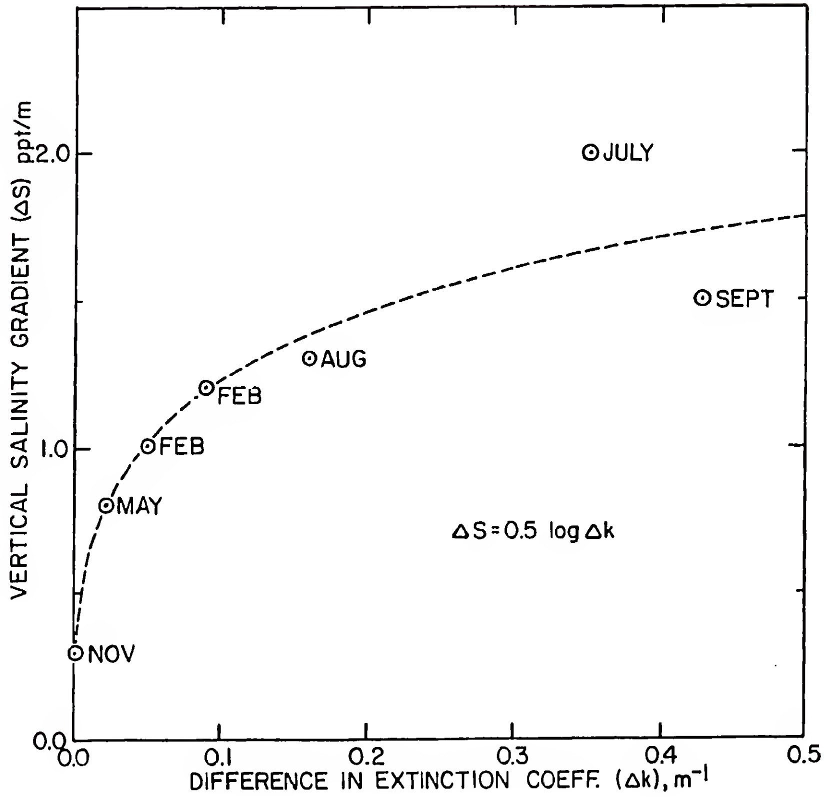

VERTICAL SALINITY GRADIENT (ΔS) ppt/m
DIFFERENCE IN EXTINCTION COEFF. (Δk), m⁻¹
0.0
1.0
2.0
0.0
0.1
0.2
0.3
0.4
0.5
JULY
SEPT
AUG
FEB
FEB
MAY
NOV
ΔS = 0.5 log Δk

Figure 41. Chlorophyll-a measurements of live plankton in canals at Crystal River power plant for 1974. Data were adapted from Gibson (1975).

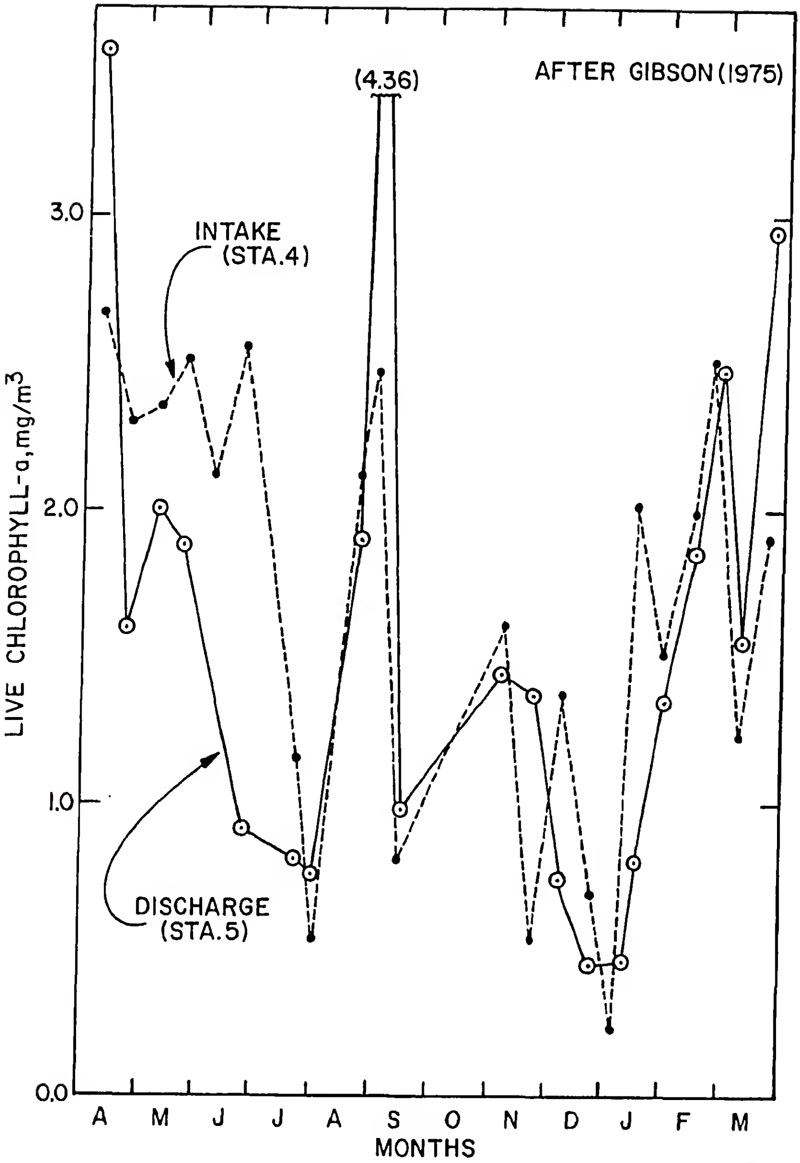

AFTER GIBSON (1975)
(4.36)
INTAKE
(STA.4)
DISCHARGE
(STA.5)
LIVE CHLOROPHYLL-a, mg/m^3
3.0
2.0
1.0
0.0
A
M
J
J
A
S
O
N
D
J
F
M
MONTHS

Figure 42. Total organic carbon of seston in canals at Crystal River power plant for 1974. Data were adapted from Gibson (1975).

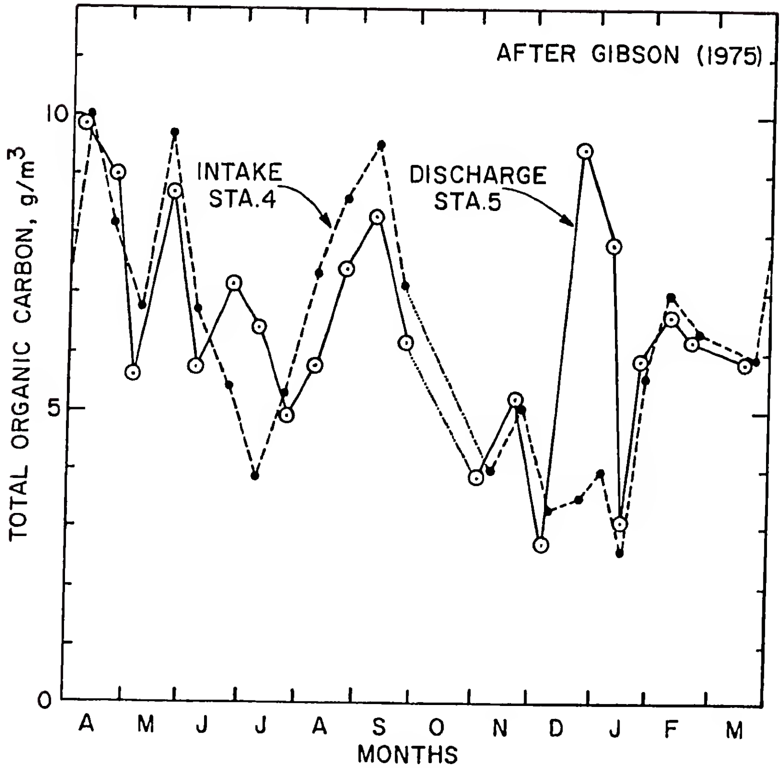

AFTER GIBSON (1975)
INTAKE STA.4
DISCHARGE STA.5
TOTAL ORGANIC CARBON, g/m³
0
5
10
A
M
J
J
A
S
O
N
D
J
F
M
MONTHS

Figure 43. Total inorganic nitrogen in canals at Crystal River power plant for 1974. Points represent $\overline{X}$, vertical bars indicate ± 1 S.E. and values above bars indicate number of samples per mean, n. Data were adapted from Gibson (1975).

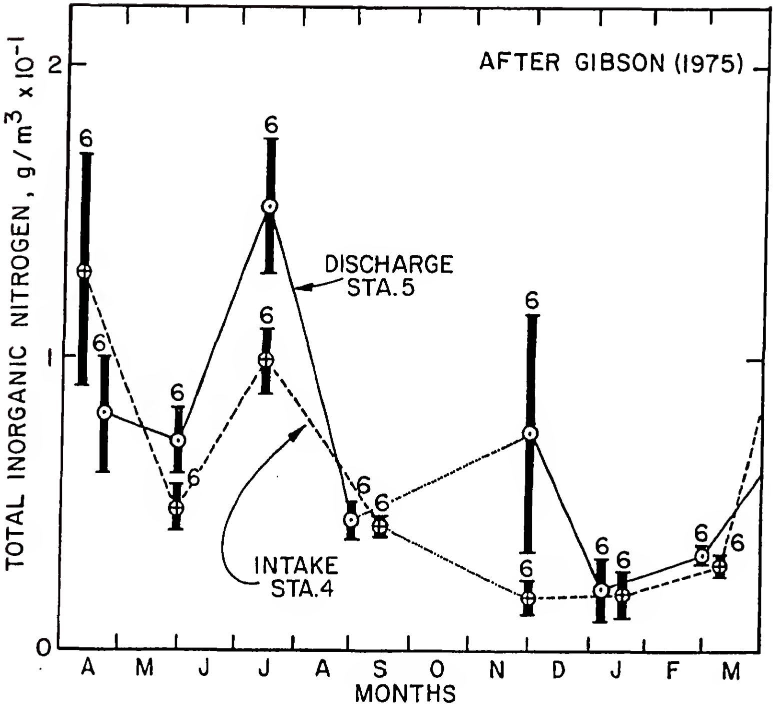
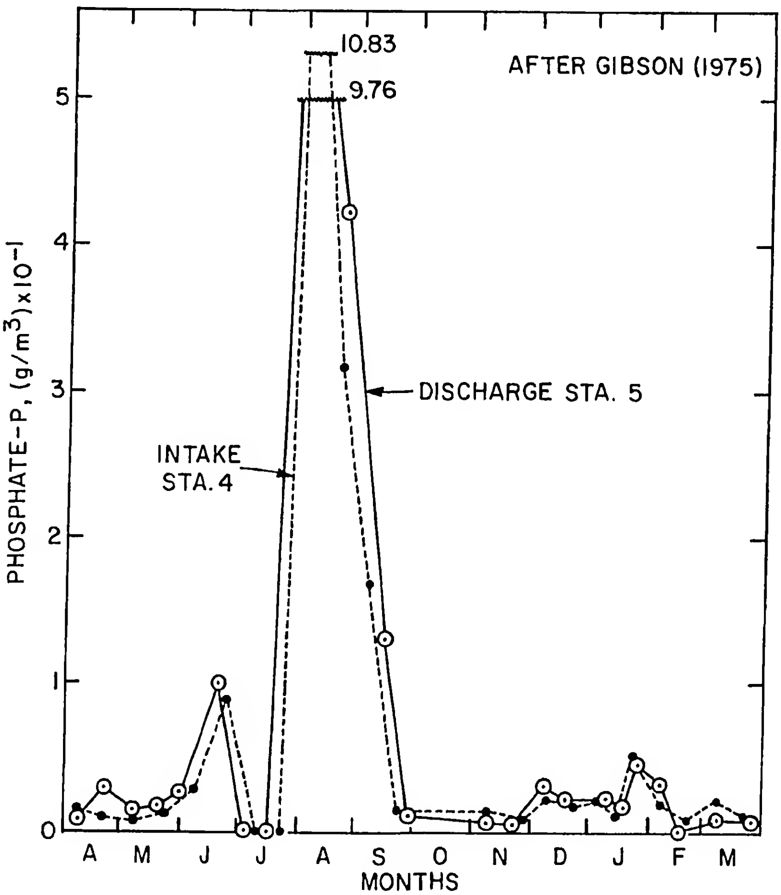

AFTER GIBSON (1975)
TOTAL INORGANIC NITROGEN, g/m^3 x 10^{-1}
0
1
2
DISCHARGE STA. 5
INTAKE STA. 4
6
A
M
J
J
A
S
O
N
D
J
F
M
MONTHS

Figure 44. Phosphate-P in canals at Crystal River power plant for 1974. Each point represents the mean of duplicate samples. Data were adapted from Gibson (1975).


10.83
9.76
AFTER GIBSON (1975)
PHOSPHATE-P, (g/m^3) x 10^{-1}
0
1
2
3
4
5
INTAKE
STA. 4
DISCHARGE STA. 5
A
M
J
J
A
S
O
N
D
J
F
M
MONTHS

early and mid summer and mid autumn periods. Inorganic nitrogen concentrations peaked in early spring, mid summer and mid autumn, again, in contrast to the chlorophyll-a blooms in mid spring, late summer and winter. Phosphate concentrations were relatively constant at less than 0.1 g/m^3 during the year except during the months of August and September when concentrations increased by an order-of-magnitude.

Structure of the Littoral Benthic Community

Data characterizing the structure of the littoral, benthic animal communities in the canals for 1973-75 are given in Tables B2-B5 of Appendix B. As with the metabolism measurements, these data were aggregated into five seasonal periods: spring; early summer; late summer; fall; and winter. In a few of the earlier samples (primarily in 1973) oyster and arthropod biomass were not measured directly but were deduced from abundance data and length-weight regressions developed in this study. Organic matter biomass of arthropods was estimated at 30% of animal whole weight as indicated from data of Day et al. (1973) and Nixon et al. (1971). Serpulid worm densities, which are given in Table B6 of Appendix B, exhibited variable patterns over the time course of this sampling. These tube worms were significantly more abundant in the intake canal during winter and spring, when numerous juveniles were encountered. For the remainder of the year there were no significant differences between the canals. Serpulid density was relatively constant in the discharge canal through the annual cycle, while significant population peaks occurred in the intake canal during late summer and winter.

Since construction of the intake and discharge canals and initial plant operation in July of 1966, ecological communities have become established in the canal systems. Macrophytes, dominated by four species of the green algal genus Caulerpa, the red alga Grassilaria sp. and the brown alga, Sargassum sp., as well as the sea grass, Halodule sp., inhabit the slopes of the intake canal at moderate densities. Epiphytic algae occur in sparse distributions in the sandy sediment and in denser mat-communities on the rocky substrate. The rocks along the steeper sloping sides of the discharge canal are encrusted with a thick algal mat community, comprised predominantly by the blue-greens, Lyngbya confervoides and L. semiplena. Relative abundance and spatial patterns of these plant communities are indicated in Table Al, and Fig. Al of Appendix A.

Aggregated Structure of Benthic Community. The salient features of community structure are illustrated in Fig. 45 (total abundance and biomass) and Fig. 46 (species diversity). Animal abundance (Fig. 45a) was significantly higher in the intake canal (95% confidence for Students' t-tests)* for all seasons except early summer. There was also greater seasonal amplitude of animal abundance in the intake canal. Mean annual abundance in the discharge canal ($1358/m^2$) was only 37% of the annual mean value for the intake canal ($3641/m^2$). However, biomass of littoral benthic animals (Fig. 45b) was slightly (3%) higher in the discharge canal (32.7 g, dry organic matter/m^2) than in the intake canal ecosystem (31.8 g/m^2) on an annual basis.

Annual trends of species diversity (= richness) for the littoral

---

* In general mean values for community structure data were tested for significant difference at 95% confidence using the Students' t-statistic unless otherwise indicated.

Figure 45. Abundance (a) and biomass (b) of animals inhabiting the littoral zone of canal ecosystems at Crystal River plant for 1974 and 1975. Points represent $\overline{X}$, vertical bars indicate ± 1 S.E. and values above bars indicate number of samples per mean, n.

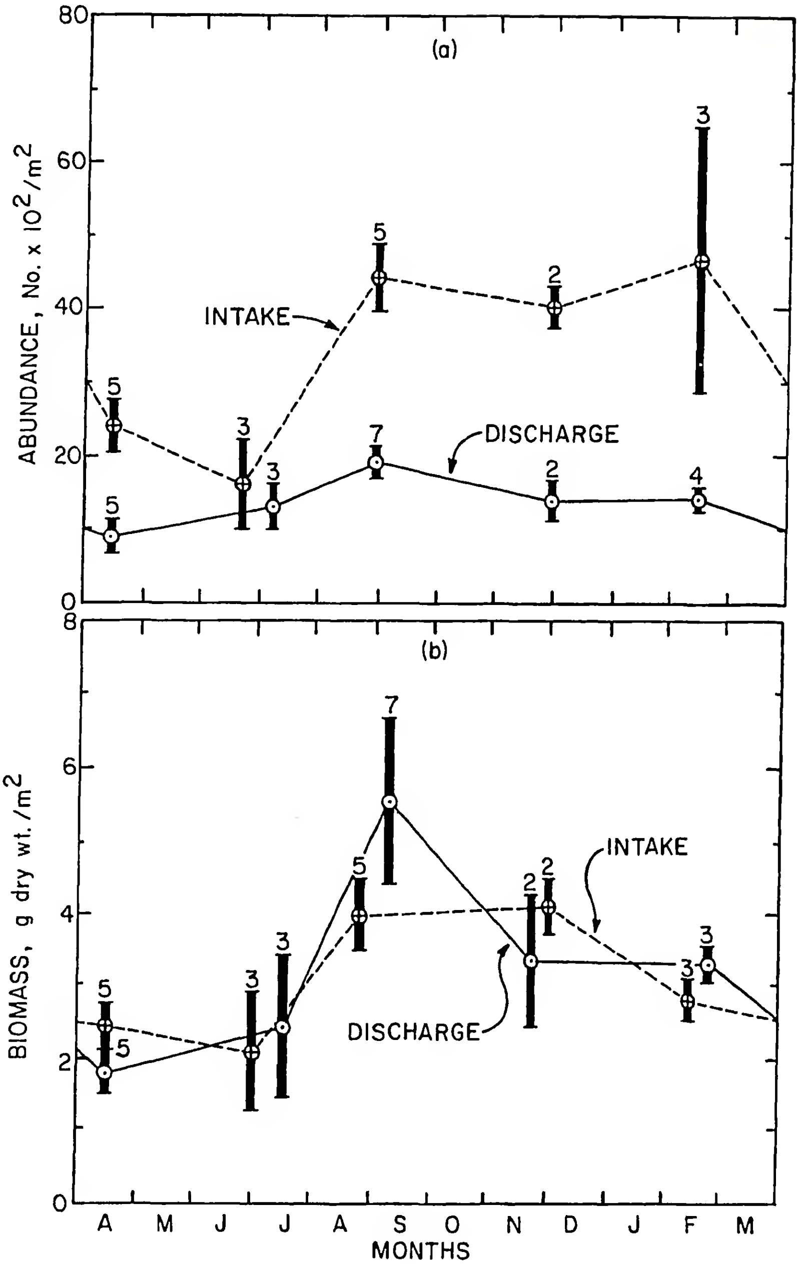
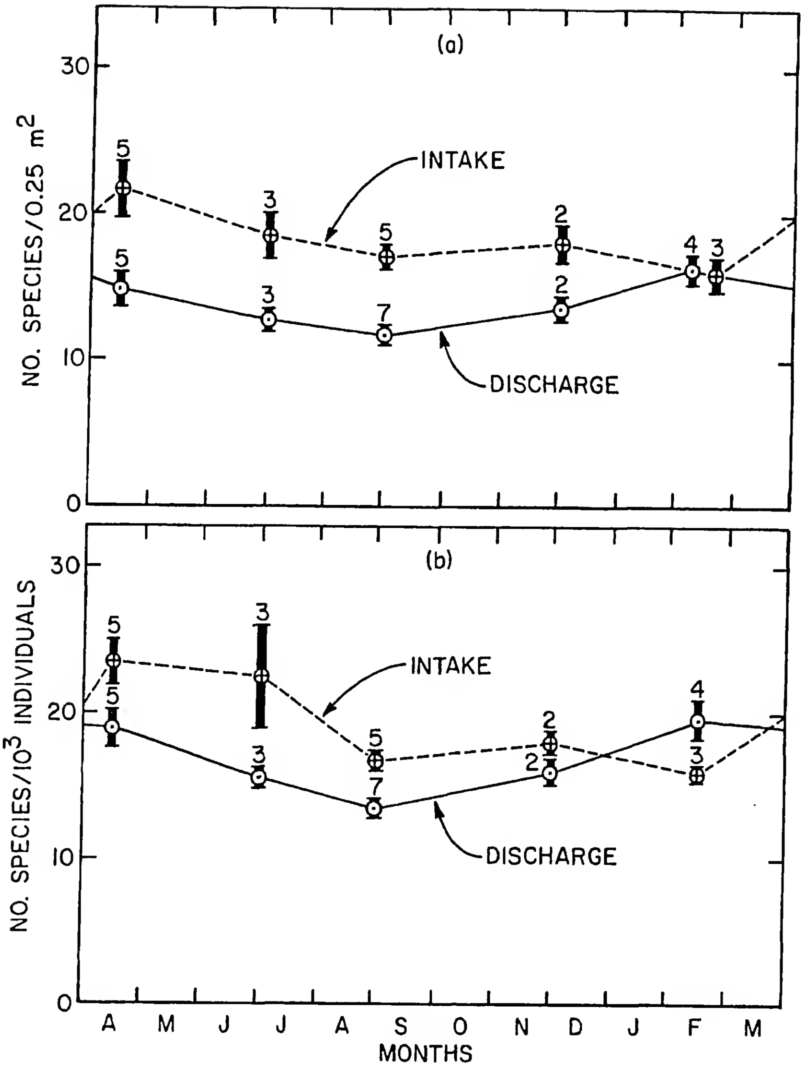

(a)
ABUNDANCE, No. x $10^2/m^2$
80
60
40
20
0
INTAKE
DISCHARGE
5
3
5
2
3
5
3
7
2
4
(b)
BIOMASS, g dry wt./m^2
8
6
4
2
0
INTAKE
DISCHARGE
5
5
3
3
5
7
2
2
3
3
A
M
J
J
A
S
O
N
D
J
F
M
MONTHS

Figure 46. Species diversity of animal communities in littoral zone of canals at Crystal River power plant for 1974 and 1975. Points represent $\overline{X}$, vertical bars indicate ± 1 S.E. and values above bars indicate number of samples per mean, n. (a) Number of species encountered in 0.25 m^2 sample; (b) Number of species encountered per 1000 individual organisms counted.


(a)
INTAKE
DISCHARGE
NO. SPECIES/0.25 m^2
0
10
20
30
5
3
5
2
4
3
5
3
7
2
(b)
INTAKE
DISCHARGE
NO. SPECIES/10^3 INDIVIDUALS
0
10
20
30
5
3
5
2
4
3
5
3
7
2
A
M
J
J
A
S
O
N
D
J
F
M
MONTHS

animal community are illustrated in two ways in Fig. 46. In Fig. 46a the number of species found per 0.25 m^2 sample is shown for the two canal ecosystems, with the intake being significantly more diverse than the discharge canal during all seasons except winter, when there was no difference. The number of species encountered per thousand individuals counted is given in Fig. 46b. Annual trends were much the same as with Fig. 46a, except that winter samples showed statistically higher diversity in the discharge than in the intake, whereas the inverse was true for the rest of the year. Both diversity parameters for both ecosystems exhibited relatively small variability between samples, as well as between seasons. All of the littoral, benthic animal species collected in this study are listed in Appendix B, Table B1 with a general notation of their relative abundance. The total number of species encountered was 58, of which 54 were found in the intake canal ecosystem while only 35 occurred in the discharge.

Dominant Organisms. Total biomass of the discharge canals' benthic littoral community was dominated by sessile filter-feeding invertebrates, Balanoid barnacles, *Balanus eburneus*, *B. improvesus*, *B. amphitrite* (40% of total) and the American oyster, *Crassostrea virginica* (27%). The major invertebrate predators on these organisms were the Xanthid mud crabs (predominantly *Eurypanopeus depressus*, *E. abbreviatus* and *Panopeus herbsti*) which themselves comprised about 27% of the community standing stocks. In the intake canal oysters and barnacles made up only 12% and 8%, respectively, of the community biomass. The dominant filter-feeder here was the mobile porcelain crab, *Pertrolisthes armatus*, whose standing stocks represented 42% of the total community. In comparison this porcelain crab constituted only 3% of the discharge canal littoral community biomass. Another suspension-feeding organism, the ribbed mussel Brachiodontus sp., showed some importance in the intake canal, comprising 3% of total compared to 0.3% in the discharge. Mud crabs were again an important predator in the intake canal representing some 26% of the total biomass. The size-class structure of the two crab groups may be indicated by the mean weight per organism. The carnivorous Xanthid crabs in the intake canal were, on the average, 3 times larger than those in the discharge canal, while porcelain crabs were about one-third as large.

Seasonal patterns of abundance and biomass for the dominant organisms in the littoral communities of the canals are given in Figs. 47, 48, and 49. Data for oyster spat density are given in Fig. 47a, showing significantly more in the intake canal than in the discharge canal through the year. Spat counts were essentially zero in the discharge canal community in spring and summer. In the intake spat concentrations were at a maximum in late summer and remained relatively numerous through the winter. In contrast, oyster biomass (Fig. 47b) was significantly more in the discharge canal in all seasons except late summer. The biomass curve for the discharge canal ecosystem was about 90° out of phase (preceeding) with the spat set. Similarly, standing stocks of Petrolisthes (Fig. 48b) were significantly greater in the intake canal with an autumn maximum. Barnacles were significantly more abundant in numbers and weight in the discharge canal than in the intake (Fig. 49). They experienced a marked late summer peak in abundance and biomass, as well as a winter maximum abundance without concommitant increase in biomass.

Figure 47. Oyster spat density (a) and adult osyter biomass in littoral zone of canals at Crystal River power plant for 1973-1975. Points represent $\overline{X}$, vertical bars indicate ± 1 S.E., and values above bars indicate number of samples per mean, n.

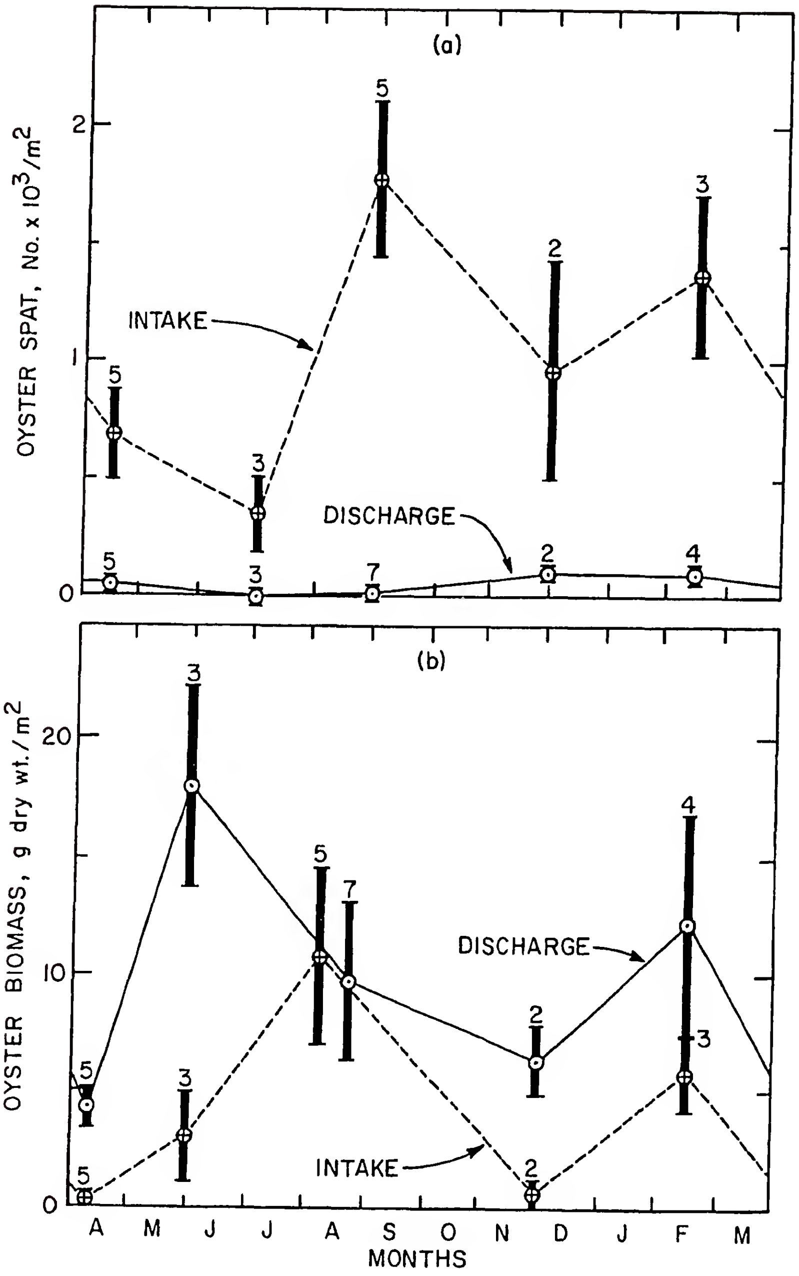

(a)
OYSTER SPAT, No. x 10³/m²
0
1
2
INTAKE
DISCHARGE
5
3
5
2
3
5
3
7
2
4
(b)
OYSTER BIOMASS, g dry wt./m²
0
10
20
DISCHARGE
INTAKE
5
3
5
7
2
4
5
3
2
3
A
M
J
J
A
S
O
N
D
J
F
M
MONTHS

Figure 48. Abundance (a) and biomass (b) of crabs in littoral zone of canals at Crystal River power plant for 1973-1975. Points represent $\bar{X}$, vertical bars indicate ± 1 S.E., and values above bars indicate number of samples per mean, n.

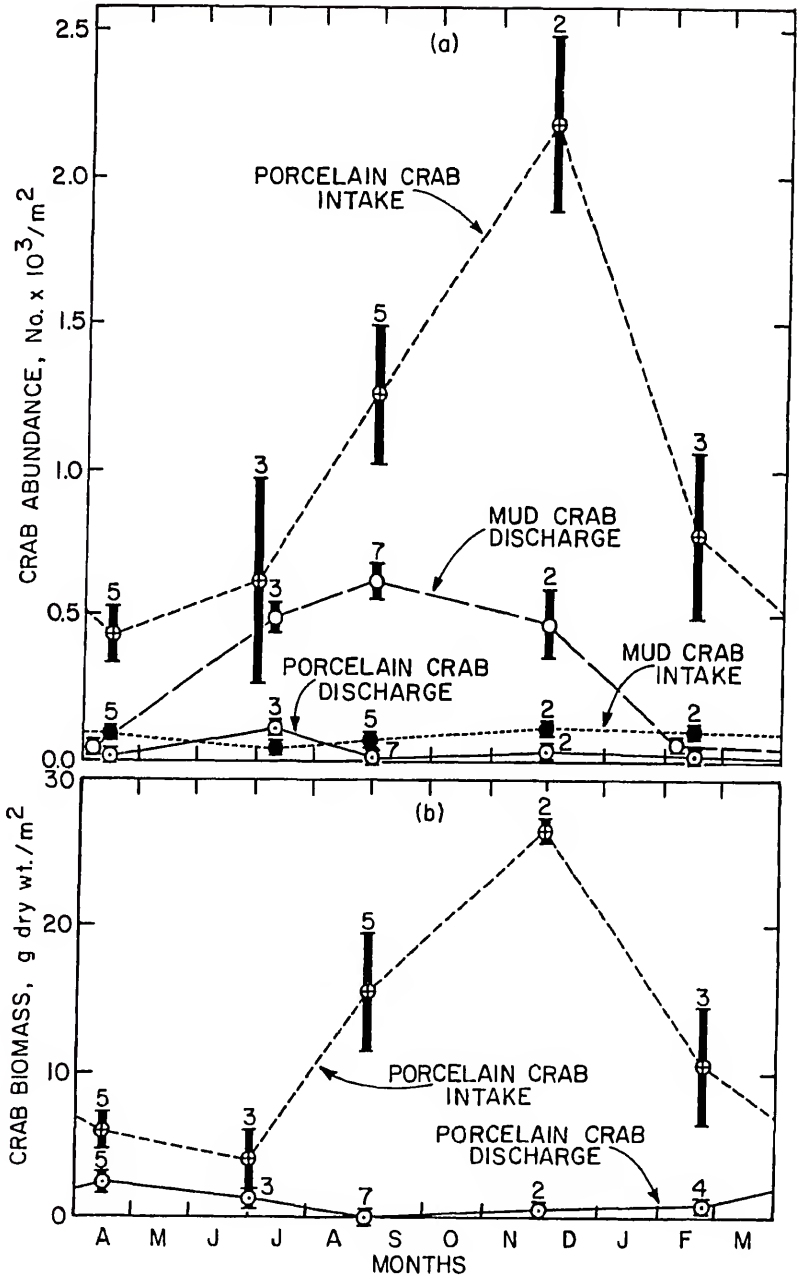
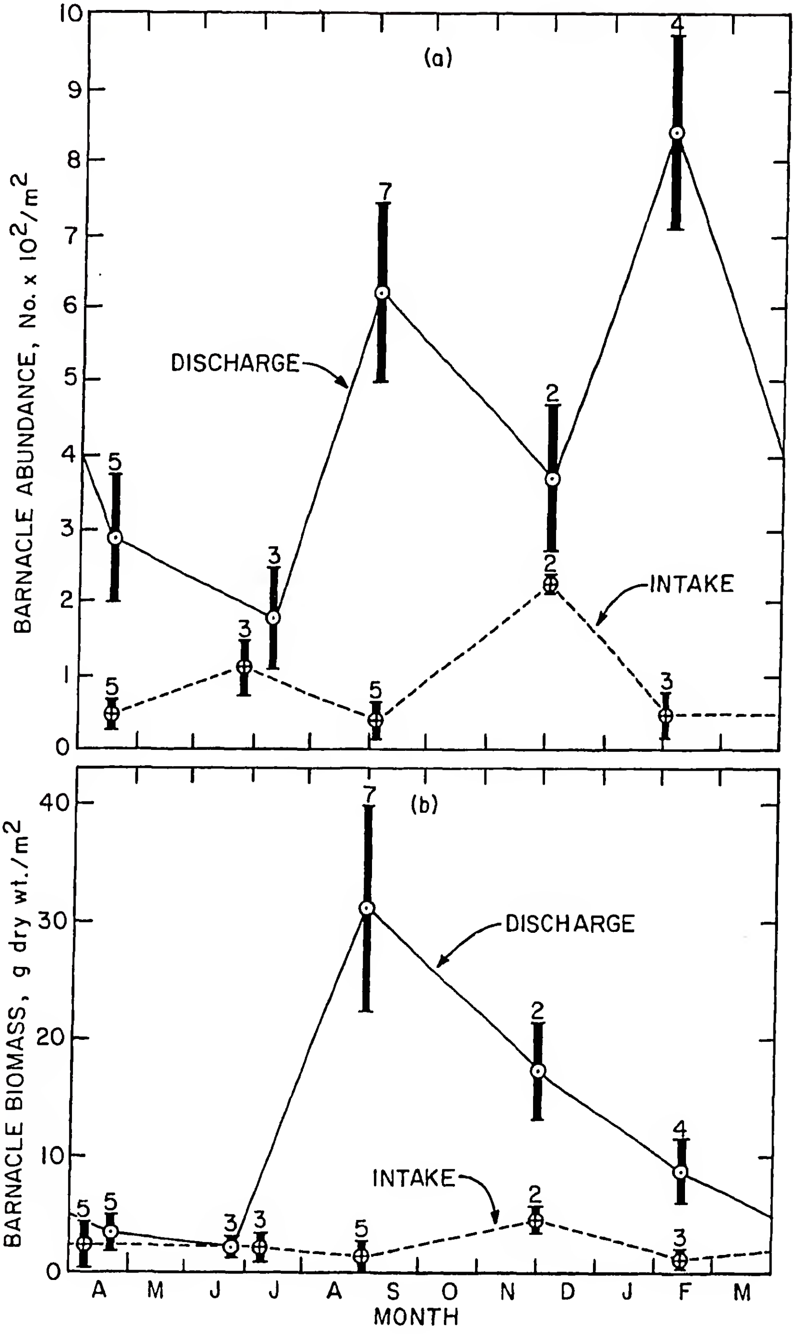

(a)
CRAB ABUNDANCE, No. x 10^3/m^2
0.0
0.5
1.0
1.5
2.0
2.5
PORCELAIN CRAB INTAKE
MUD CRAB DISCHARGE
MUD CRAB INTAKE
PORCELAIN CRAB DISCHARGE
5
3
5
2
3
7
(b)
CRAB BIOMASS, g dry wt./m^2
0
10
20
30
PORCELAIN CRAB INTAKE
PORCELAIN CRAB DISCHARGE
4
A
M
J
J
A
S
O
N
D
J
F
M
MONTHS

Figure 49. Abundance (a) and biomass (b) or barnacles in littoral zone of canals at Crystal River power plant for 1973-1975. Points represent $\bar{X}$, vertical bars indicate ± 1 S.E. and values above bars indicate number of samples per mean, n.


(a)
BARNACLE ABUNDANCE, No. x $10^2/m^2$
10
9
8
7
6
5
4
3
2
1
0
DISCHARGE
INTAKE
5
3
7
2
4
5
3
5
2
3
(b)
BARNACLE BIOMASS, g dry wt./m^2
40
30
20
10
0
DISCHARGE
INTAKE
7
2
4
5
5
3
3
5
2
3
A
M
J
J
A
S
O
N
D
J
F
M
MONTH

The Nekton Community: Structure and Movements

Blue Crabs in the Intake Canal. The blue crab, *Calinectes sapidus*, populations in the intake canal were estimated by analysis of mark-recapture data collected by Oesterling (1973, 1976; Adams et al., 1974), using a modified form of the Peterson type catch-ratio formula to account for emigration of marked crabs from the canal. Oesterling's (1976) data documented the movement of blue crabs into and out of the canal ecosystem, as well as onto the power plant intake screens. Twenty-four crabs captured and marked in the canal were later recaptured outside of the intake canal ecosystem, four marked crabs were found impinged on the power plant screens, and one crab marked outside the canal was later recovered in canal station traps. In Appendix D of this dissertation a formula was developed for estimating the canal's blue crab population, taking into account effects of migration on the number of marked crabs.

A total of 2050 crabs were marked (m_b) in Oesterling's bay stations. Of these 139 were recaptured (r_b) either in the bay area or elsewhere. In the intake canal 528 crabs were captured (C_c), and of these 13 were recaptures (r_c) so that a total of 515 marked crabs (m_c) were placed in the canal. As previously indicated, 7 crabs marked inside the canal were recaptured outside (r_{bn}), and one crab marked outside was recaught inside (r_{cn}). The 4 marked crabs impinged by the power plant suggest that 4 x 7 or 28 marked crabs in all were probably caught on the intake screens (J_{ms}), since screens were monitored only once per week. Therefore, the estimate of annual mean blue crab population in the canal was $N_c = 16.9 \times 10^3$, which is equivalent to a density of about 0.046 crabs/m^2. For this population estimate, the standard error (Eq. (20), Methods section) is 4.6×10^3, which is about

27% of N_c. To check the importance of the migration correction, the above computation of N_c is compared to a population estimate using the standard Peterson formula where,

$$N = \frac{(515)(528)}{13} = 20.9 \times 10^3 \quad .$$

In this case, ignoring migration lead to an overestimate by 23%.

Monthly blue crab catch data are summarized in Table 30, which is used to generate cumulative population estimates in the canal according to Eq. (19) in Methods section. The resulting estimate is very low (2310), and this is to be expected because of the low monthly recapture rates in the canal, the largest being 3. As indicated previously, with $r_c < 7$ this method produces negatively biased results, and therefore this is a poor population estimate. Emigration was calculated using the proportionality in Eq. (21) of the Methods section using values for N_c, m_c, r_{bn}, r_b and m_b given in the previous paragraph. Thus, it was found,

$$J_{Nb} = J_{mb}(N_c/m_c) = 110\ (16937/515) = 3.6 \times 10^6 \text{ crabs/yr} \quad .$$

Similarly, immigration was calculated with Eq. (22) of the Methods, where it was assumed that: (1) crab population densities were about the same in the bays as in the canal ($0.046/m^2$); and (2) that the bay area contributing marked crabs to the canal was outlined by the trap locations ($17 \times 10^6\ m^2$). Thus, immigration was estimated as $J_{bN} = 15.5 \times 10^3$ crabs/yr. Since recaptures in the bay did not begin to appear until 2 mos after initial markings, it was considered that only 10 mos of data on immigration into the canal were actually monitored. Thus, a more realistic estimate might be (12/10) times J_{bN} or

Table 30. Summary of monthly blue crab catch data for estimate of canal population using Schnabel-type cumulative mark-recapture analysis.*

Month	Captures		Recaptures		Impingement	
	Bay m_b	Canal C_c	Bay $r_b(r_{bn})$	Canal $r_c(r_{cn})$	J_{ms}	$\overline{m}_c \cdot C_c$
1973						
Oct.	101	96	1	3	1	8256
Nov.	151	84	0	3	0	6804
Dec.	88	29	2	0	0	0
1974						
Jan.	299	45	49	0	1	0
Feb.	255	44	36	2	0	1310
Mar.	135	38	33	0	0	0
Apr.	247	71	12	1	1	2707
May	462	105	2	3	0	10,710
Jun.	171	0	4	0	1	0
Jul.	71	0	0	0	0	0
Aug.	70	16	0	1	0	240
Sept.	0	0	0	1	0	0
Oct.	0	0	0	0	0	0
Totals	2050	528	139	13	4	30,027

$$N_c = \sum (\overline{m}_c \cdot C_c) / \sum r_c = 2310$$

---

* Data from Oesterling (1973, 1976). See Appendix D for explanation of abbreviations in column headings.

18.7×10^3 crabs/yr, which amounts to about 0.737 g organic matter/$m^2 \cdot$yr.

Batfish in the Intake Canal. Detailed data from measurements of population density of polkadot batfish, *Ogcocephalus radiatus*, are given in Appendix C and summarized in Table 31. Using the Petersen-type formula given previously as Eq.(15), estimates of batfish populations (N) were made. For the north bank of the intake canal, N = $(316)(308)/8 = 12.2 \times 10^3$ fish, excluding the last day's tagging which had no opportunity for recaptures. According to Dorman and Sutton (1973) approximately one-half of the total canal length was surveyed in their study, so that the north bank population is probably more like $2 \times 12{,}166 = 24.3 \times 10^3$ batfish. The south bank was apparently less densely populated, and only 77 fish were caught and tagged in seven dives (11 per dive) compared to 348 in eleven dives (32 per dive) on the north bank. All dives were approximately the same length of time (90 min.), and assuming that fishing pressure was the same during each dive, the population on the south bank can be estimated at 24,332 (11/32) = 8364 fish. Thus, the total batfish population in the bilaterally confined canal was about 32.7×10^3 fish, or approximately 0.089 fish per m^2. Using equation (3) the etandard error of this estimate is about ± 11,265 fish which is 34% of the mean.

Notice in Table C2 of Appendix C that there were two recaptures of tagged fish in zone 3 on September 28 before any batfish had been tagged in that zone. Since 166 fish had already been tagged in zone 4, it can be assumed that these two recaptures in zone 3 were probably derived from fish tagged in zone 4. Assuming that rate of movement was a function of population density as with Eq. (21) of Methods the migration (J_{N43}) of batfish along the north bank from zone 4 to zone 3

Table 31. Summary estimates of population density of polkadot batfish, *Ogcocephalus radiatus*, in the intake canal ecosystem at Crystal River.[a]

Date 1973	Measurement Method	Location	Density number/hectare
Sept. 19-29	Mark-Recapture[c]	Bilaterally confined canal	890
Oct. 3	SCUBA Surveys[b]	Bilaterally confined canal	370
Oct. 4 & 10	"	Open Bays	0.8
Oct. 11	"	Outer canal without south spoil bank	340

[a] Data from Dorman and Sutton (1973), by permission. See Appendix C for details and text for calculation.

[b] SCUBA counts from 24 transects in which 40 fish were observed.

[c] Mark and recapture done by SCUBA on 18 dives over 7 day period.

can be estimated as

$$J_{N43} = J_{m43}(N_4/m_4) \tag{45}$$

where J_{m43} is movement of marked fish from zone 4 to 3, and N_4 and m_4 are zone 4 populations of total fish and marked fish, respectively. The batfish population in zone 4 (N_4) can be estimated from data in Table C2 again using equation (21),

$$N_4 = (166)(161)/5 = 5.3 \times 10^3 \text{ batfish} \quad .$$

Again assuming, as indicated by Dorman and Sutton (1973), that only half the bank was surveyed the actual population would be closer to 5345 x 2 = 10.7 x 10^3 fish. Therefore migration along the north bank was

$$J_{N43} = 2(10{,}690/166) = 129 \text{ fish/day} \quad .$$

If, as before, it is assumed that the south bank population was proportional to the north bank population times the differential catch/effort between the two banks, the total migration on an annual basis would be 63,270 fish/yr.

Data from SCUBA censuses of transects done in October 1973 for estimating batfish population densities are given in Table C2. Each transect covered about 100 m^2 and there were 24 transects in all, 11 in the canal and 13 in the adjacent bays. Batfish populations were estimated at $0.037/m^2$ in the bilaterally confined canal and $0.034/m^2$ in the outer canal with only one spoil bank, while the population in the bay was to be negligible. Batfish were more common on sandy, gravel sediments with some rocks and were virtually absent from soft mud substrates with or without vegetation. In Table 31 the various batfish population estimates are summarized. The mark-recapture calculation compares reasonably well with the transect observations in the canal, and the mean of the three canal population calculations is 533 ± 179 fish/ha.

Gill-Netting of Fish in Canal Ecosystems. Data describing fish populations of the canal ecosystems, as sampled by gill netting in March and June of 1975, are given in Table C3 of Appendix C. During the winter sample midnight water temperatures were 20.7°C and 25.0°C in the intake and discharge canals, respectively, while the summer study at 1800 hr, temperatures were 30.4°C and 36.6°C. A total of 714 fish weighing (fresh weight) 580 kg (1270 lb) were caught in the 4 nights of sampling. Of this total catch, 75% (by weight) was taken in the discharge canal during the March sample. The catch in the intake canal was dominated by jack crevalle, Caranx hippos (39%), particularly during the summer. Other important species included: longnose gar, Lepisosteus oculatus (14%); gaftopsail catfish, Bagre marinus (10%); blacktip shark, Carcharhinus limbatus (9%); and stingrays, Dasyatis spp. (8%). With the exception of catfish, these other species occurred almost exclusively in the winter sample. The gill-net catch in the discharge canal was comprised primarily of two organisms: crevalle jack, Caranx hippos (62%) and gaftopsail catfish, Bagre marinus (31%).

This gill-netting data is then summarized in Table 32, where standing stocks and movements of fish are given on an area-weighted basis for comparison between the two canals and with other ecosystems. Standing stocks were higher in both canals on the March sample, with the discharge canal biomass being 2.8 times as great as in the intake canal. The seasonal difference in the intake canal ecosystem, however, is

Table 32. Summary of gill-netting estimates of nekton populations in canal ecosystems at Crystal River power plant.

Ecosystem	Date (1975)	Resident[a] or Transient	Abundance Number/ha	Biomass kg fresh/ha	Movement, kg fresh/ha-day	
					In	Out
Intake Canal	Mar 19	Resident	87	61.6	0.9	0.5
		Transient	8	0.6	---	---
	June 25	Resident	44	21.2	0.4	1.0
		Transient	46[b]	17.6[b]	1.4	0.4
	Mean	Resident	66	41.4	0.7	0.8
		Transient	27	9.1	1.4	0.4
Discharge Canal	Mar 20	Resident	208	158.4	4.6	2.6
		Transient	10[b]	18.0[b]	26.6	19.3
	June 26	Resdient	40	7.2	0	0
		Transient	0	0	0	0
	Mean	Resident	124	82.8	2.3	1.3
		Transient	5	9.0	13.3	9.7

[a] Residents defined as populations whose migration time-constant was generally > 50 days; transients are those populations whose migration time-constant was generally < 10 days.

[b] Includes estimate of diurnal immigrants as part of standing stocks.

probably not significant (62.2 g fresh/m^2 in March vs. 38.8 g fresh/m^2 in June) considering the variability of fish populations in the Crystal River area (Adams, 1974; Homer, 1976). In the discharge canal ecosystem the winter standing stocks (176.4 g/m^2) were 24.5 times greater than in the summer sample (7.2 g fresh/m^2) when effluent water temperatures approached 37°C. Catfish (primarily Bagre marinus) and crevalle jack (Canax hippos) were the dominant organisms contributing to nekton biomass. The major organisms netted in the intake canal standing stock measurement were jack in the summer and winter and the blacktip shark (Carcharhinus limbatus) in the winter.

Estimations of migration rates were based on organisms caught moving in and out of canals during time period of sample, divided by the area of canal. The highest migration rates were for the crevalle jack in the discharge canal during March (in = 25.8 g fresh/$m^2 \cdot$day; out = 17.2 g fresh/$m^2 \cdot$day). The migration turnover, τm, of nekton populations (standing stock/migration rate) ranged from about 1-100 days for species which were netted. Based on these migration turnover times of each species, the nekton of the canal ecosystems fell generally into two population categories, "transients" (having $\tau_m < 10$ days) and "residents" ($\tau_m > 50$ days). Generally, the schooling fish (mullet, herring, silversides) and roving predators (jack, gar, sharks, mackerel) were considered as "transient" components of the pelagic nekton, while the "resident" nekton was comprised primarily by such species as catfish, spadefish, sheepshead, and drum.

It appeared in the winter sample that jack and gar would move freely in and out of the discharge canal such that they could replace their standing stocks within the canal ecosystem in less than a day.

However, these "transient" nekton comprised only 10% of the total canal fish population. No movements of fish were recorded in the discharge during the summer. In the intake canal ecosystem, transient populations comprised over 45% of the total for the summer, but less than 1% for the winter sample, and migration was more important in the summer.

A conspicuous absence from the gill net catches was that of the striped mullet, Mugil cephalus, even though it is known to be an important schooling herbivore in this area (Homer, 1976). Only 4 mullet were captured in the gill nets during this study (3 of these were partially eaten), and they were observed on almost every sampling excursion (for this entire study) jumping, and feeding on epiphytes and detritus along the canal banks. Mullet are known to have excellent skills for avoiding gill nets (Wagner, 1973). A total of 29 species were netted in the intake canal on the two sampling occasions, while only 9 species were encountered in the discharge canal samples. All fish species found in this gill netting study are listed in Table C1 of Appendix C.

Trophic Habits of Selected Canal Nekton. The results of analyses of stomach contents for selected fish caught in the gill netting studies of canal ecosystems are given in Table C5, of the Appendix, and these are summarized in Table 33. In all, the contents of 40 individual fish stomachs were examined for March and June samples (mostly from the intake canal). Most of the organisms analyzed were feeding on fish and invertebrates. Jack crevalle, Caranx hippos, was found to be almost exclusively a piscivore, with the exception of three shrimp removed from jack stomachs. Their primary identifiable food sources were the silversides, Menidia spp. The gafftopsail catfish, Bagre marinus, was a mixed invertebrate and fish-feeder. One 400 mm SL catfish had a

Table 33. Summary of trophic habits observed for selected fish caught by gill net in canals at Crystal River power plant.

Ecosystem	Species	No. of Stomachs Examined	Stomach Contents, % (wt.)		
			Fish	Shrimp	Benth. Invert.
Intake Canal	*Caranx hippos*	14	95[b]	5	0
	Bagre marinas	6[c]	58	9	33
	Carcharhinus limbatus	4	94[d]	0	6
	Dasyatis spp.	2	0	67	33
	Other Carnivores[a]	g[f]	59	31	10
Discharge Canal	*Pogonias cromis*	3	0	10	90[h]
	Archosargus orobatocephalus	1	0	0	100

[a] Includes following species: *Pomatomus saltatrix*; *Haemulon plumieri*; *Orthopristic chrysoptera*; *Paralichthys albigutta*; *Elops saurus*; *Cynoscion nebulosus*; *Pogonias cromis*.

[b] Mostly *Menidia sp*.

[c] Stomach conetnts included: *Anguilla*; *Opsanus*; Xanthid and *Petrolisthes* crabs.

[d] Fish include: Gobiidae; *Cynoscion*; *Pogonias*; *Elops*; Clupeids.

[e] Mostly oyster shells.

[f] Stomach contents include: *Chloroscombrus*; Gobiidae; Xanthid and *Petrolisthes* crabs; Nassa snails; Polychaeta; *Upogebia*.

[g] Stomach contents include: Xanthid and *Petrolisthes* crabs; *Upogebia*; Nassa snails.

390 mm SL eel, Anguilla sp., occupying its tomach. Seatrout, ladyfish, and bluefish were all piscivores although only one of each was examined. A prime carnivore of the canal ecosystems was the blacktip shark, Carcharhinus limbatus, whose diet consisted of varied fish species. Many of the shark's prey were themselves piscivores (e.g., seatrout and ladyfish), making the shark, in part, a third of fourth level carnivore. The diets of black drum and sheepshead were comprised entirely of benthic invertebrates.

The intestines of a single mullet were analyzed, and diatoms, miscellaneous plant material, and detritus were found along with the encrusting sponge, Haliclona sp. Unformtunately, there were insufficient data to indicate any differences between feeding habits in the two canals. Jack crevalle in the intake canal was the only species examined with enough frequency to consider seasonal differences. However, in both March and June samples jack was primarily piscivorous although its prey was identifiable only in the winter specimens.

Evaluated Model: Summary of Data for Canal Ecosystems

Field data, assembled data and estimates, collected to describe the canal ecosystems at Crystal River are summarized in Fig. 50 for summer (a) and winter (b) conditions. Animal components in this model were organized according to general trophic habit and habitat, applying information given in Tables 33 and 37. Benthic invertebrates are grouped into three trophic types: (1) suspension-feeders such as oysters, barnacles and porcelain crabs; (2) deposit-feeders such as polychaetes and mud snails; and (3) predatory animals such as mud crabs. Nekton are also grouped into three types: (1) herbivores and detritivores such

Figure 50. Detailed energy diagrams illustrating primary components of intake and discharge canal ecosystems interacting with power plant and external estuary. Ecosystem components are grouped into subsystems corresponding to Fig. 31. They relate directly to field data reported in this study, and are evaluated for summer (a) and winter (b) conditions at Crystal River. Abbreviations and units of measure used to report data are as follows:

S = Sunlight, $kcal/m^2 \cdot day$

T = TEMP = Temperature, °C

PHOS = Phosphate, $g\ P/m^3$

NITR = Inorganic nitrogen, $g\ N/m^3$

PHYT = Phytoplankton, $g\ org/m^3$

ZOOP = Zooplankton, $g\ org/m^3$

WDET = Seston, $g\ org/m^3$

BDET = Sediment detritus, $g\ org/m^2$

BAUTO = Benthic autotrophs, $g\ org/m^2$

DINV = Deposit-feeding benthic invertebrates, $g\ org/m^2$

SINV = Suspension-feeding benthic invertebrates, $g\ org/m^2$

CINV = Predatory benthic invertebrates, $g\ org/m^2$

HBN = Herbivorous nekton, $g\ org/m^2$

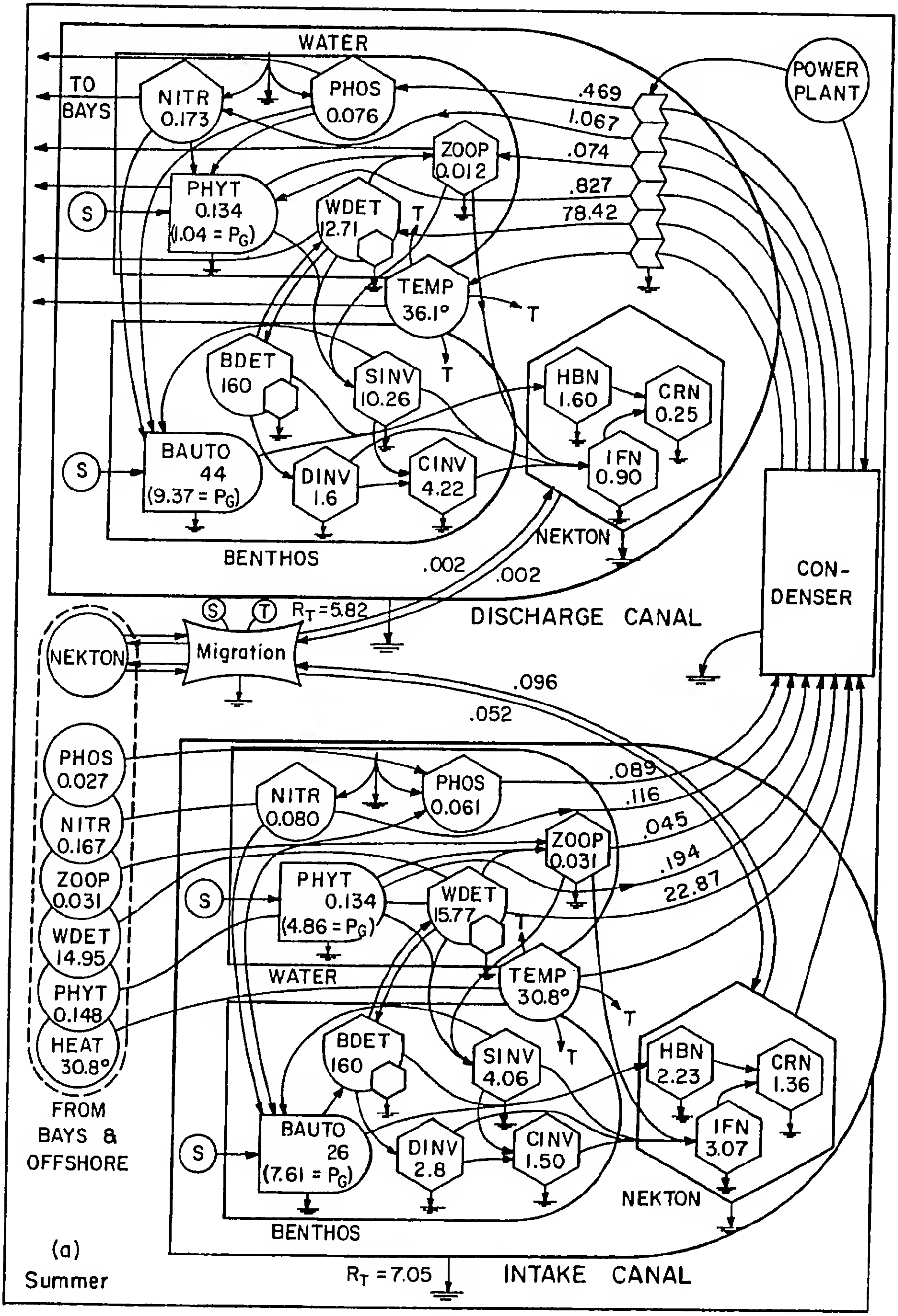
IFN = Benthic-feeding nekton, $g\ org/m^2$

CRN = Piscivorous nekton, $g\ org/m^2$

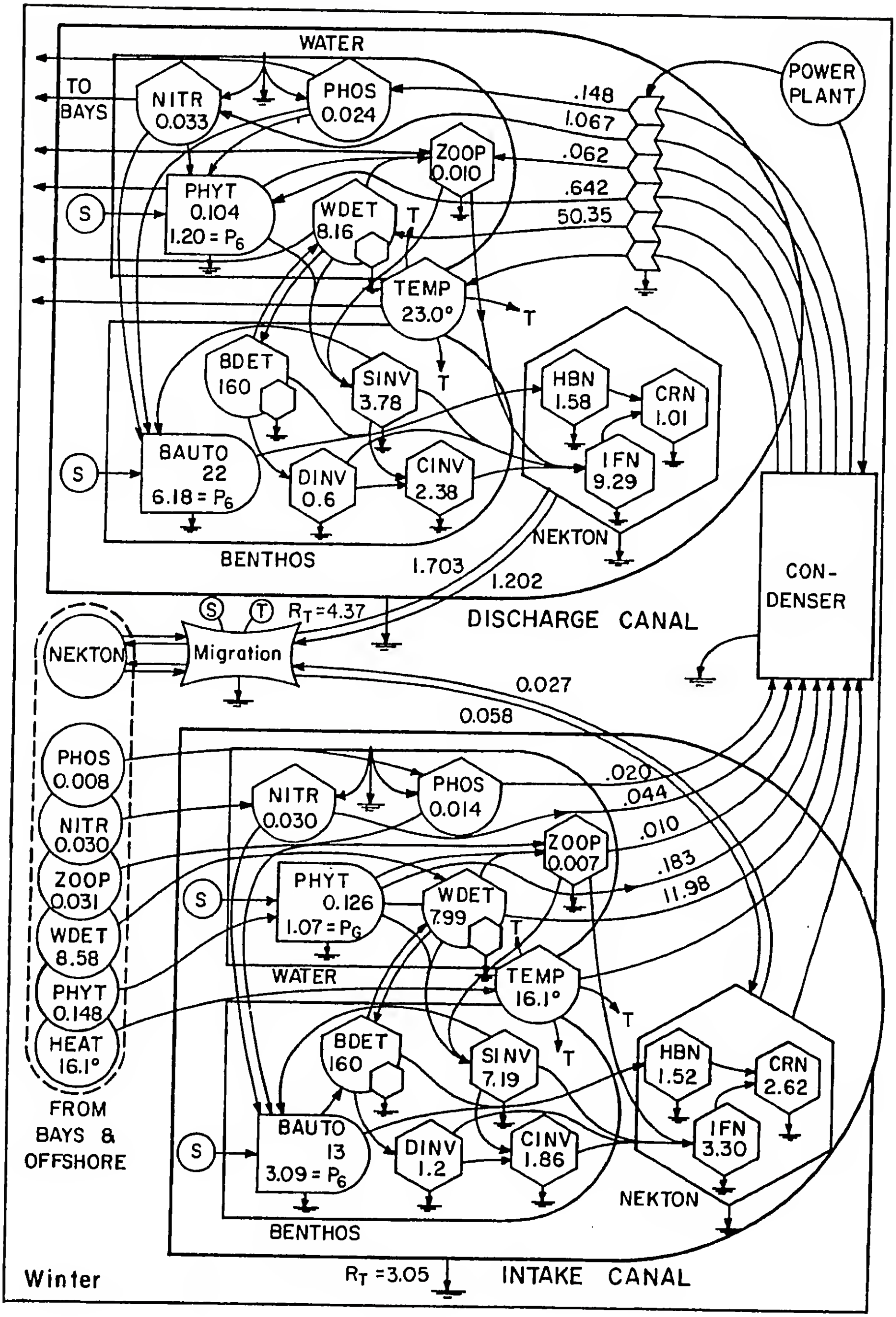
P_G = Gross productivity

R_T = Total community respiration

Flows are per day.


WATER
TO BAYS
NITR 0.173
PHOS 0.076
POWER PLANT
.469
1.067
.074
.827
78.42
ZOOP 0.012
PHYT 0.134 (1.04 = P_G)
S
WDET 12.71
T
TEMP 36.1°
T
T
BDET 160
SINV 10.26
HBN 1.60
CRN 0.25
BAUTO 44 (9.37 = P_G)
S
DINV 1.6
CINV 4.22
IFN 0.90
NEKTON
BENTHOS
.002
.002
CON-DENSER
S
T
R_T = 5.82
DISCHARGE CANAL
NEKTON
Migration
.096
.052
PHOS 0.027
NITR 0.167
ZOOP 0.031
WDET 14.95
PHYT 0.148
HEAT 30.8°
FROM BAYS & OFFSHORE
NITR 0.080
PHOS 0.061
.089
.116
.045
.194
22.87
ZOOP 0.031
S
PHYT 0.134 (4.86 = P_G)
WDET 15.77
T
WATER
TEMP 30.8°
T
T
BDET 160
SINV 4.06
HBN 2.23
CRN 1.36
S
BAUTO 26 (7.61 = P_G)
DINV 2.8
CINV 1.50
IFN 3.07
NEKTON
BENTHOS
R_T = 7.05
INTAKE CANAL

(a)
Summer


WATER
TO BAYS
NITR 0.033
PHOS 0.024
ZOOP 0.010
PHYT 0.104 1.20 = P6
WDET 8.16
T
TEMP 23.0°
T
T
S
.148
1.067
.062
.642
50.35
POWER PLANT
BDET 160
SINV 3.78
HBN 1.58
CRN 1.01
S
BAUTO 22 6.18 = P6
DINV 0.6
CINV 2.38
IFN 9.29
NEKTON
BENTHOS
1.703
1.202
CON- DENSER
S
T
RT=4.37
DISCHARGE CANAL
NEKTON
Migration
0.027
0.058
PHOS 0.008
NITR 0.030
ZOOP 0.031
WDET 8.58
PHYT 0.148
HEAT 16.1°
FROM BAYS & OFFSHORE
NITR 0.030
PHOS 0.014
.020
.044
ZOOP 0.007
.010
.183
11.98
S
PHYT 0.126 1.07 = P6
WDET 7.99
T
WATER
TEMP 16.1°
T
T
BDET 160
SINV 7.19
HBN 1.52
CRN 2.62
S
BAUTO 13 3.09 = P6
DINV 1.2
CINV 1.86
IFN 3.30
NEKTON
BENTHOS
Winter
RT =3.05
INTAKE CANAL

Footnotes to Fig. 50.

1) Plankton Production:

Intake, summer = 4.86 g org/m^2·day (Table 28)

winter = 1.07 " "

Discharge, summer = 1.04 " "

winter = 1.20 " "

2) Benthic Production:

Intake, summer = 7.61 " $= P_{total} - P_{phyto}$ (Tables 27 & 28)

winter = 3.09 " "

Discharge, summer = 9.37 " "

winter = 6.18 " "

3) Community Respiration:

Intake, summer = 7.05 " (Table 27)

winter = 3.05 " "

Discharge, summer = 5.82 " "

winter = 4.37 " "

4) Nekton migration:

Intake, summer -

Immigr = 0.096 g org/m^2·day (Table 32)

Emigr. = 0.052 " "

winter -

Immigr. = 0.058 " "

Emigr. = 0.027 " "

Discharge, summer -

Immigr. = 0.002 g org/m^2·day (Table 32)

Emigr. = 0.002 " "

Footnotes to Fig. 50. (Continued)

Discharge, winter -

Immigr. = 1.703 g org/m^2·day (Table 32)

Emigr. = 1.202 " "

5) Water and material flows through power plant:

Intake canal turns-over 1.45/day (Carder et al., 1974a)

Discharge canal turns-over 6.17/day (Carder et al., 1974b)

PHOS:

Intake, summer = 0.089 g P/m^2·day (Fig. 44)

winter = 0.020 " "

Discharge, summer = 0.469 " "

winter = 0.148 " "

NITR:

Intake, summer = 0.116 g N/m^2·day (Fig. 43)

winter = 0.044 " "

Discharge, summer = 1.067 " "

winter = 0.204 " "

WDET:

Intake, summer = 22.87 g/m^2·day (Fig. 42)

winter = 11.58 " "

Discharge, summer = 78.42 " "

winter = 50.35 " "

PHYT:

Intake, summer = 0.194 g/m^2·day (Fig. 41)

winter = 0.183 " "

Discharge, summer = 0.827 " "

winter = 0.642 " "

Footnotes to Fig. 50. (Continued)

ZOOP:

Intake, summer = 0.045 g/m^2·day (Fig. 20)

winter = 0.010 " "

Discharge, summer = 0.074 " "

winter = 0.062 " "

6) NITR, Inorganic Nitrogen Concentration:

Intake, summer = 0.167 (sta. 1), 0.080 (sta. 4) g/m^3 (Fig. 43)

winter = 0.030 " 0.030 " " "

Discharge, summer = 0.182 (sta. 5), 0.163 (sta. 7) " "

winter = 0.027 " 0.033 " " "

7) PHOS, Phosphate Concentration:

Intake, summer = 0.027 (sta. 1), 0.061 (sta. 4) g/m^3 (Fig. 44)

winter = 0.008 " 0.014 " " "

Discharge, summer = 0.063 (sta. 5), 0.076 (sta. 7) " "

winter = 0.019 " 0.024 " " "

8) PHYT, Phytoplankton concentration:

Assume C/Chl-a = 50 (Parsons et al., 1961).
Assume org/C = 2 (E.P. Odum, 1971).

Intake, summer = 0.148 (sta. 1), 0.134 (sta. 4) g org/m^3 (Fig. 41)

winter = 0.078 " 0.126 " " "

Discharge, summer = 0.134 (sta. 5), 0.194 (sta. 7) " "

winter = 0.088 " 0.104 " " "

9) WDET, Seston Concentration:

Intake, summer = 14.95 (sta. 1), 15.79 (sta. 4) g org/m^3 (Fig. 42)

winter = 8.58 " 7.99 " " "

Discharge, summer = 12.97 (sta. 5), 12.71 (sta. 7) " "

winter = 11.09 " 8.16 " " "

Footnotes to Fig. 50. (Continued)

10) ZOOP, Zooplankton Concentration:

Intake, summer = 0.031 g org/m^3 (Fig. 20)

winter = 0.007 " "

Discharge, summer = 0.021 (sta. 5), 0.012 (sta. 7) g org/m^3 "

winter = 0.022 " 0.010 " " "

11) TEMP, Temperature: (Table 27)

Intake, summer = 30.8°C

winter = 16.1°C

Discharge, summer = 36.1°C

winter = 23.0°C

12) BDET, Detrital Sediments:

Assume specific gravity of sediments to be 2.65 (Chow, 1964).
Assume upper 2 mm biologically active, aerobic (Kanwisher, 1962).
Assume organic content of sediments to be 3% (Cottrell, 1974).

$$\text{Intake} = \text{Discharge (summer, winter)} = 2.65\ \text{g/cm}^3(.03\ \text{organic})$$

$$\times\ (10^6\ \frac{\text{cm}^3}{\text{m}^3})(.002\ \text{m}) = 160\ \text{g org/m}^2$$

13) BAUTO, Benthic Autotrophs:

Assume (C/Chl-a) = 50 (Parsons et al., 1961).

Discharge, summer

$$\text{Benthic Chl-a} = (1.12\ \text{g Chl-a/m}^2)(100\ \text{g org/g Chl-a})$$

$$= 112\ \text{g org/m}^2, \text{ littoral (Kemp, this study)}$$

Assume biomass in channel to be 10% of that in littoral zone, based on qualitative microscopic examinations. Littoral zone is about 33% of discharge canal area, and 20% of intake canal area; 40% of intake canal is essentially devoid of benthic plants (main channel). Assume winter standing stock to be 50% of summer stocks.

$$\text{Total plant matter} = 112\ (.33) + 11\ (.67) = 44\ \text{g org/m}^2$$

Footnotes to Fig. 50. (Continued

Discharge, winter = 22 g org/m^2

Intake, summer = 112(.20) + 11(.40) = 26 g org/m^2

winter = 13 g org/m^2

14) SINV, Suspension-Feeding Benthic Invertebrates:

Includes barnacles, mussels, oysters, porcelain crabs (Newell, 1970; MacGinnitie and MacGinnitie, 1968). Assume biomass in channel of intake canal is 1 g/m^2 and in discharge canal is 2 g/m^2.

Intake, summer = 4.06 g org/m^2 (Tables B3, B4, B5)

winter = 3.78 " "

Discharge, summer =10.26 g org/m^2 "

winter = 7.19 " "

15) CINV, Predatory Benthic Invertebrates: primarily Xanthid crabs (Green, 1968)

Intake, summer = 1.50 g org/m^2 (Table B4)

winter = 1.86 " "

Discharge, summer = 4.22 " "

winter = 2.38 " "

16) DINV, Deposit-Feeding Benthic Invertebrates: includes gastropods, and polychaetes (Kemp, this study)

Intake, summer = 2.8 g org/m^2

winter = 1.2 "

Discharge, summer = 1.6 "

winter = 0.6 "

17) HBN, Herbivore-Detritivore Nekton: includes mullet, spadefish (Jones, 1964)

Intake, summer = 2.3 g org/m^2

winter = 1.52 "

Discharge, summer = 1.60 "

winter = 1.58 "

Footnotes to Fig. 50. (Continued)

18) IFN, Benthic-Feeding Nekton: includes catfish, drum, sheepshead (Hellier, 1962; McFarland, 1963; Tables 31 and 32, this study)

Intake, summer = 3.07 g org/m^2

winter = 3.30 "

Discharge, summer = 0.90 "

winter = 9.29 "

19) CRN, Predatory Nekton: includes jack, sharks, gar (Table 32)

Intake, summer = 1.36 g org/m^2

winter = 2.62 "

Discharge, summer = 0.25 "

winter = 1.01 "

as mullet and spadefish; (2) invertebrate-feeders including both planktivores such as herring and anchovies, and benthic-feeders such as sheepshead and black drum; and (3) piscivorous nekton such as sharks, jack and gars.

In the summarized form of Fig. 50, the general annual patterns of major ecosystem components of the intake and discharge canals can be viewed simultaneously for comparison. Gross community productivity was 17% higher in the intake than the discharge canal during the summer, but was 44% higher in the discharge canal during the winter. Plankton productivity represented 39% and 26% of total productivity of the intake canal for summer and winter, respectively, but was only 11% and 16% of the total in the discharge canal. Mean phytoplankton standing stocks were variable month-to-month but were not very different between canals or among seasons. Zooplankton were substantially fewer in the discharge than the intake during the summer, but were virtually the same in either system during the winter. Seston concentrations during the summer were lower in the discharge than in the intake, whereas in the summer seston was nearly the same in both canals. Mean concentrations of inorganic nutrients were higher in the discharge canal for both summer and winter, but this difference between canals was smaller during the winter.

Suspension-feeding invertebrates were the dominant benthic group in both canals for both seasons, ranging from 56-64% of total standing stocks in the discharge and 48-72% in the intake. Total benthic invertebrate biomass was higher in the intake canal during the winter. Total nekton stocks follow the same patterns as exhibited in community productivity, with intake canal being higher in the summer and discharge canal being higher in the winter. Invertebrate-feeding nekton were dominant in the discharge canal in the winter at the same time that invertebrate stocks were relatively sparse in that ecosystem. The other two categories of nekton were generally constant for both canals for both seasons, except that piscivorous nekton were virtually absent from the discharge canal during the summer sample. Nekton migration was relatively unchanged for the two seasons in the intake canal, ranging from 0.027-0.096 g dry/m^2·day. However, in the discharge canal it was nearly 3 orders of magnitude higher in winter than summer (1.703 compared to 0.002 g dry/m^2·day).

Quality of Natural Energies at Crystal River

In this section the ability of four naturally occurring types of energy to accomplish work is compared to that of coal.

Energy Quality of Coastal Waves

Given in Table 34 are technical data describing 43 beach nourishment projects involving the U.S. Corps of Engineers between 1923 and 1952. Figures for the cost of dredging probably underestimate the true costs because much of the pre-dredging engineering work was done by the government-subsidized Corps of Engineers. However, the vast majority of actual dredging operations were conducted by private companies under open-bid contracts. The costs per cubic yard were relatively variable, and probably reflected the distance which dredged material was transported, the kind of material, and the method employed, as well as local economic factors. The major interactions involved in the countercurrent processes of natural, longshore transport of sand and mechanical nourishment of eroded beaches are depicted in Fig. 51. In the most general sense the movement of sand results from both "suspension transport" (due only to wave breaking) and "bedload transport" (due to wave, tide and wind-induced currents) according to Bruun (1973). However, within the 10 m depth contour (which is the active ground for beach erosion) virtually all littoral drift is generated by wave forces (Bruun, 1973; Bascom, 1964).

The mechanical work done by the dredging operations was calculated as force times distance. It was assumed in all cases that the specific gravity and porosity of sand were 2.65 and 0.6, respectively, as given

Table 34. Summary of beach nourishment projects sponsored by U.S. Corps of Engineers and comparison of local wave energies with dredging costs.[a]

Location and date	Distance from fill ft x 10^4	Amount dredged yd^3 x 10^6	Wave[b] energy, E_A, kcal x 10^9	Work[c] of sand transpt, kcalx10^9	Ratio sand transpt: wave E_A	Dredging costs, $/$yd^3$	1967[d] dredge costs $ x 10^6	Dredge[e] energy kcal CE x 10^9	Ratio dredge energy: wave E_A
Santa Bbra, Ca. 1935	1.06	.202	2.7	1.84	.68	.15	.073	2.0	.74
" 1938	.53	.606	3.5	2.76	.79	.21	.306	8.3	2.37
" 1940	.53	.698	4.0	3.18	.80	.178	.296	8.0	2.00
" 1942	.53	.600	3.5	2.75	.79	.219	.269	7.3	2.09
" 1945	.53	.718	4.1	3.27	.80	.237	.316	8.5	2.07
" 1947	.53	.643	3.7	2.93	.79	.17	.163	4.4	1.19
" 1949	.53	.838	4.6	3.81	.83	.192	.225	6.1	1.33
" 1952	.53	1.174	6.1	5.34	.88	.26	.384	10.4	1.70
Port Hnme, Ca. 1939	.27	1.450	3.8	3.36	.88	.20	.697	18.8	4.95
" 1943	.27	.175	0.6	0.41	.68	.20	.068	1.8	3.00
Santa Monica, Ca. 1950	.13	1.000	1.3	1.12	.86	.25	.347	9.4	7.23
Venice, Ca. 1945	2.90	.150	5.6	3.73	.67	.67	.186	5.0	.89

Table 34. (Continued)

Location and date	Distance from fill ft x 10^4	Amount dredged yd^3 x 10^6	Wave[b] energy, E_A, kcal x 10^9	Work[c] of sand transpt, kcalx10^9	Ratio sand transpt: wave E_A	Dredging costs, $\$/yd^3$	1967[d] dredge costs \$ x 10^6	Dredge[e] energy kcal CE x 10^9	Ratio dredge energy: wave E_A
El Segundo, Ca. 1948	1.90	14.00	186.4	228.4	1.23	.265	5.146	138.9	.75
Redondo, Ca. 1947	1.58	.090	2.0	1.22	.61	1.00	.135	3.7	1.85
Cabrillo, Ca. 1927	1.32	.500	7.4	5.67	.77	.20	.192	5.2	.70
" 1948	1.32	2.886	33.1	32.71	.97	.40	1.601	43.2	1.31
Long Beach, Ca. 1942	2.64	4.00	87.9	90.66	1.03	.14	1.148	31.0	0.35
" 1946	2.64	4.00	87.9	90.66	1.03	.14	.957	25.8	0.29
Anaheim Bay, Ca. 1947	1.58	1.097	17.3	14.88	.86	.23	.377	10.2	0.59
Newport Bay, Ca. 1935	0.79	7.09	44.3	48.09	1.09	.20	3.536	95.5	2.16
Mission Bch, Ca. 1948	1.32	0.625	9.1	7.08	.78	.21	.182	4.9	0.54
Ocean Bch, Ca. 1949	1.32	0.064	1.2	.73	.61	.17	.015	0.4	0.33

Table 34. (Continued)

Location and date	Distance from fill ft x 10^4	Amount dredged yd^3 x 10^6	Wave[b] energy, E_A, kcal x 10^9	Work[c] of sand transpt, kcalx10^9	Ratio sand transpt: wave E_A	Dredging costs, \$/yd^3	1967[d] dredge costs \$ x 10^6	Dredge[e] energy kcal CE x 10^9	Ratio dredge energy: wave E_A
Ocean Bch, Ca. 1950	1.32	0.067	1.2	.76	.63	.17	.016	0.4	0.33
Coronado Bch, Ca. 1939	0.32	3.50	9.7	9.62	.99	.15	1.262	34.1	3.52
" 1942	1.32	19.00	169.6	215.3	1.27	.125	4.867	131.4	0.77
Hampton Bch, N.H. 1935	0.29	0.535	2.0	1.33	.67	.25	.334	9.0	4.50
N. Haven, Ct. 1948	0.95	1.00	9.4	8.16	.87	.75	1.040	28.1	2.99
Cntr Is, L.I., NY 1947	0.26	0.507	1.5	1.13	.75	.37	.280	7.6	5.07
Orchard Bch, NY 1937	0.21	0.078	0.4	.14	.35	.69	.131	3.5	17.50
Jacb Rile L.I., NY 1939	0.53	0.400	2.5	1.82	.73	.15	.144	3.9	1.56
Coney Is, NY 1923	0.34	1.700	5.4	4.96	.92	.21	.711	19.2	3.56
Atlantic Cty, NJ 1948	0.24	0.50	1.3	1.03	.79	.77	.534	14.4	11.07

Table 34. (Continued)

Location and date	Distance from fill ft x 10^4	Amount dredged yd^3 x 10^6	Wave[b] energy, E_A, kcal x 10^9	Work[c] of sand transpt, kcalx10^9	Ratio sand transpt: wave E_A	Dredging costs, $\$/yd^3$	1967[d] dredge costs $\$$ x 10^6	Dredge[e] energy kcal CE x 10^9	Ratio dredge energy: wave E_A
Atlantic Cty, NJ 1948	0.40	0.70	3.0	2.40	.80	.77	.748	20.2	6.73
Ocean City, NJ 1952	0.82	1.92	14.5	13.37	.92	.75	1.793	48.4	3.33
" 1952	0.82	1.08	8.9	7.60	.85	.60	.814	22.0	2.47
" 1939	1.32	0.60	8.6	6.80	.79	.14	.202	5.5	0.64
" 1952	0.16	6.00	7.7	8.24	1.07	.135	1.031	27.8	3.67
Mean (Excluding Florida)			20.7	22.6	0.83			22.3	2.87
Palm Bch, Fl. 1948	0.58	0.63	4.0	3.14	.79	.193	.169	4.6	1.15
" 1948	0.58	1.035	6.0	5.15	.86	.193	.277	7.5	1.25
" 1948	0.58	0.455	3.0	2.26	.75	.193	.122	3.3	1.10
" 1944	0.58	0.30	2.1	1.49	.71	.35	.199	5.4	2.57
" 1948	0.58	0.216	1.3	1.07	.82	.322	.096	2.6	2.00
Lake Worth, Fl. 1950	0.05	0.09	0.1	.03	.30	.12	.015	0.4	4.00

Table 34. (Continued)

Location and date	Distance from fill ft x 10^4	Amount dredged yd^3 x 10^6	Wave[b] energy, E_A, kcal x 10^9	Work[c] of sand transpt, kcalx10^9	Ratio sand transpt: wave E_A	Dredging costs, \$/yd^3	1967[d] dredge costs \$ x 10^6	Dredge[e] energy kcal CE x 10^9	Ratio dredge energy: wave E_A
Mean Florida			2.8	2.19	.71			4.0	2.01
Mean for all data			18.2	19.80	0.82			19.7	2.75

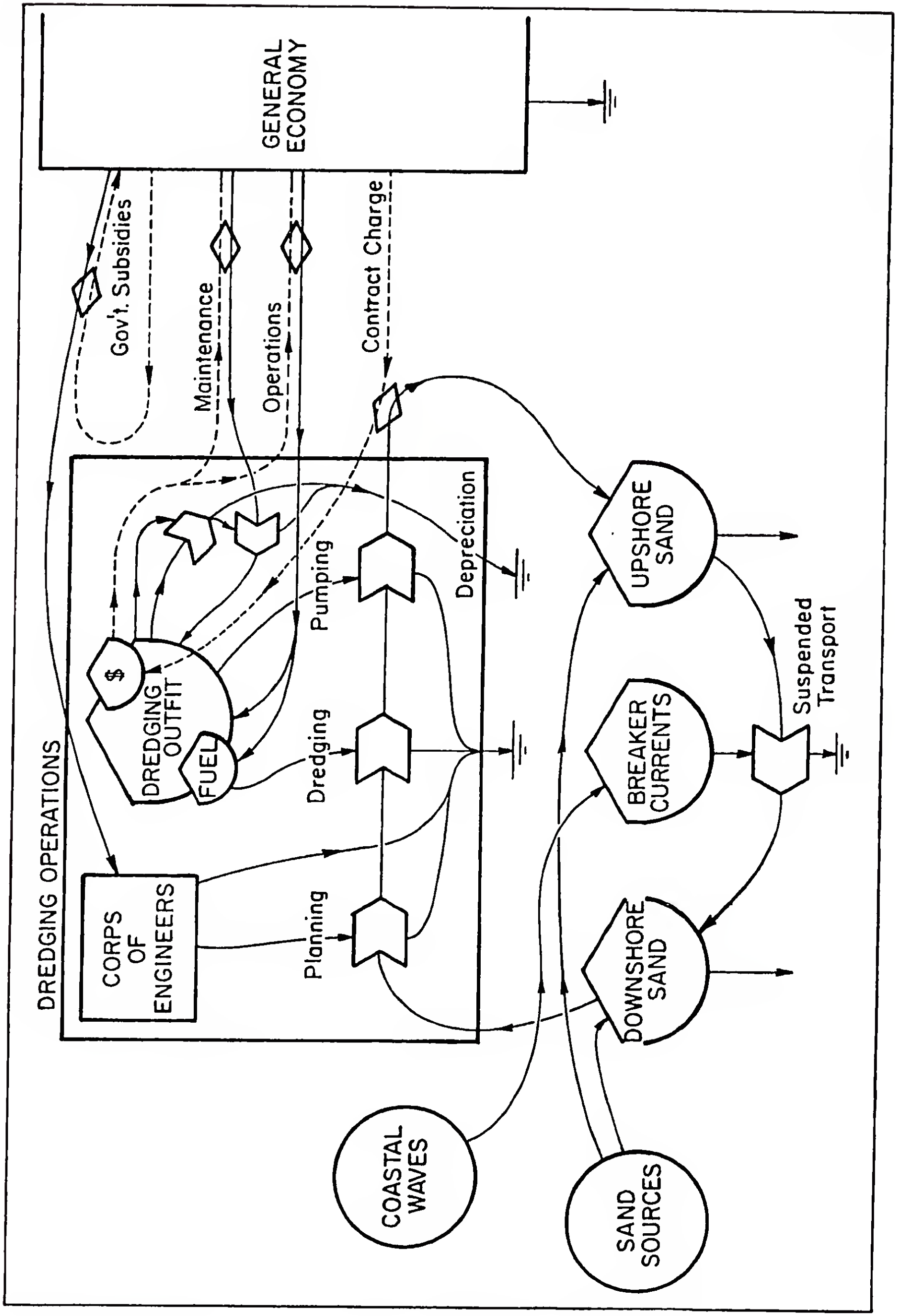
[a] Data taken from Hall (1952) and Wiegel (1964).

[b] Alongshore wave energy, E_A, needed to transport sand estimated from regressions reported in Walton (1973), Ingle (1966), Bruun (1973), and Bascom (1964).

[c] Mechanical work of sand transport, assuming specific gravity = 2.65, porosity = 0.6 for a specific wt. of 2683 lb/yd^3 (Chow, 1964).

[d] Estimated from energy/dollar ratio for U.S. in 1967 = 27,000 kcal CE/\$ (Kylstra, 1974).

Figure 51. Diagrammatic model of major interactions involved in the counter-current processes of natural longshore transport of sand and mechanical nourishment of eroded beaches.

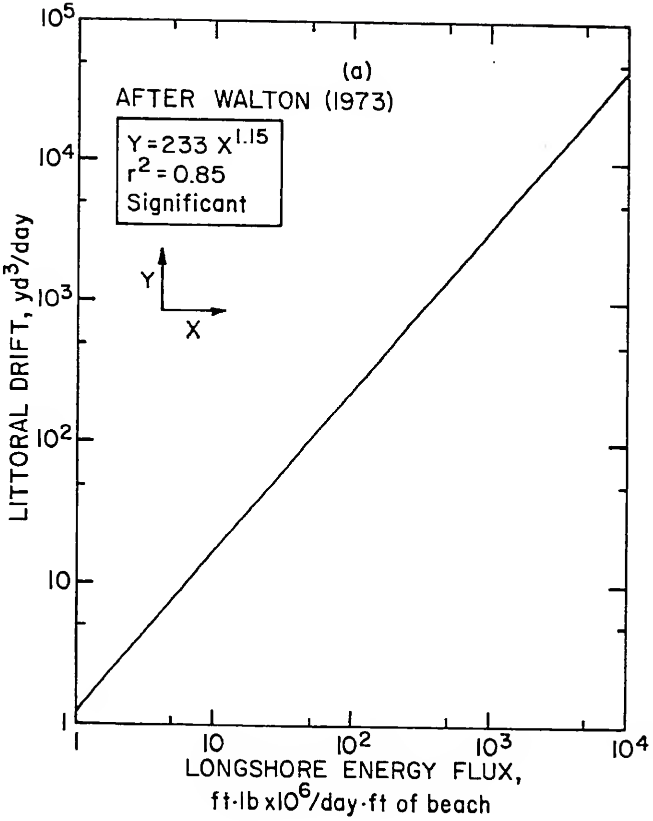

GENERAL ECONOMY
Gov't. Subsidies
Maintenance
Operations
Contract Charge
DREDGING OPERATIONS
$
DREDGING OUTFIT
FUEL
CORPS OF ENGINEERS
Planning
Dredging
Pumping
Depreciation
UPSHORE SAND
BREAKER CURRENTS
DOWNSHORE SAND
Suspended Transport
COASTAL WAVES
SAND SOURCES

in Chow (1964). Beach nourishment may be done using continuous dredging methods or slug dredging which might take anywhere from a few months to several years, but these calculations were made on an annual basis. The annual wave energy (along shore component, E_A) needed to move an amount of sand equivalent to that dredged was estimated from a regression equation calculated with various data given by Walton (1973). This regression, given as Fig. 52a, is highly significant with $r^2 = 0.85$. The 117 data points presented by Walton are from numerous investigators, and 9 of these (from Fairchild, 1966; and from Caldwell, 1956) were not included in the regression because experimental designs and assumptions appeared to render them less realistic for the general considerations of this analysis.

It can be seen in Fig. 52b that the cost of dredging and the alongshore component of wave energy were significantly related by a power function. The data are moderately scattered having a coefficient of determination, $r^2 = 0.64$. With the energy cost of dredging given in "coal equivalents" (CE), this function may indicate the energy quality of waves. Since the exponent of the independent variable (cost of dredging) is less than 1.0 it appears that the quality of wave energy may decrease as the magnitude of wave energy increases. This apparent relationship is examined further in Fig. 53a, where the ratio of dredging energy cost to wave energy parallel to shore (energy quality ratio) is plotted against the magnitude of wave energy. This is basically a scatter diagram with a very weak inverse relationship is exhibited (not significant at 95% confidence, $r^2 = 0.20$).

However, it may be that the true relationship between magnitude of wave energy and its ability to do work is masked in Fig. 53a by the so

Figure 52. (a) Regression of longshore wave energy, E_A, versus littoral drift based on data given by Walton (1973) taken from numerous authors. Data from Fairchild (1966) and Caldwell (1956) not included here because of uncertain sources. There were 108 data points used to derive this relationship.
(b) Relationship between the alongshore wave energy needed to transport a given quantity of sand and the energy cost of dredging to return same amount of sand at same rate. Data is taken from Table 34, where dredging energy is estimated from dollar costs for beach nourishment.


(a)
AFTER WALTON (1973)
Y=233 X^1.15
r^2 = 0.85
Significant
Y
X
LITTORAL DRIFT, yd^3/day
10^5
10^4
10^3
10^2
10
1
1
10
10^2
10^3
10^4
LONGSHORE ENERGY FLUX,
ft·lb x10^6/day·ft of beach

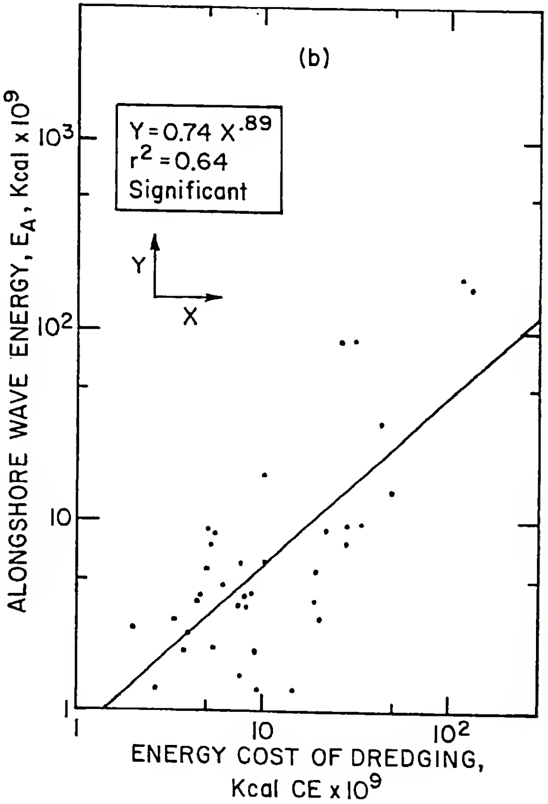
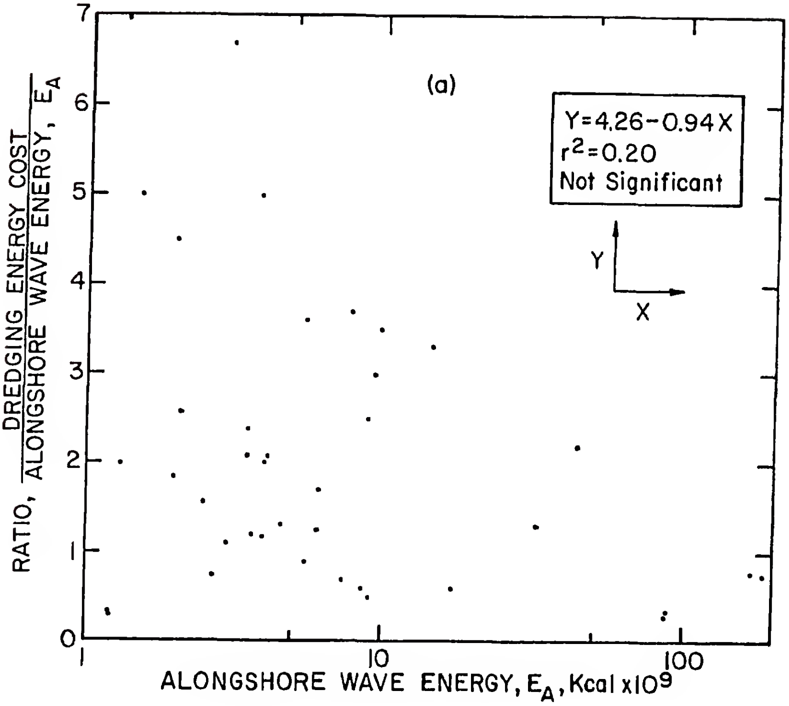
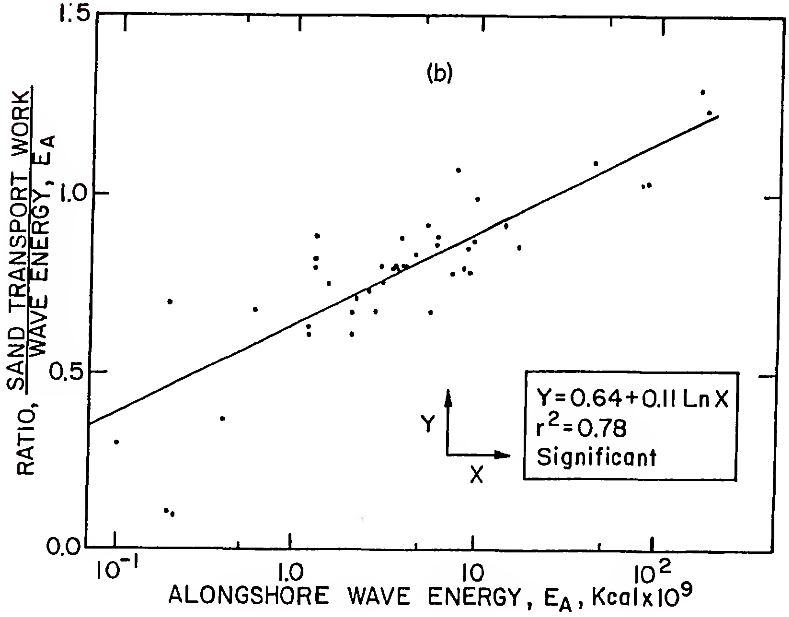

(b)
Y=0.74 X^.89
r^2 = 0.64
Significant
Y
X
ALONGSHORE WAVE ENERGY, E_A, Kcal x 10^9
10^3
10^2
10
1
1
10
10^2
ENERGY COST OF DREDGING,
Kcal CE x 10^9

Figure 53. (a) Scatter diagram showing very weak inverse relationship between alongshore wave energy, E_A, and the ratio of dredging costs to E_A.
(b) Diagram showing relationship between the amount of transport work accomplished per unit of wave energy and the total wave energy involved. Data are from Table 34.


(a)
Y=4.26−0.94X
r^2=0.20
Not Significant
Y
X
RATIO, DREDGING ENERGY COST / ALONGSHORE WAVE ENERGY, E_A
0
1
2
3
4
5
6
7
1
10
100
ALONGSHORE WAVE ENERGY, E_A, Kcal x10^9

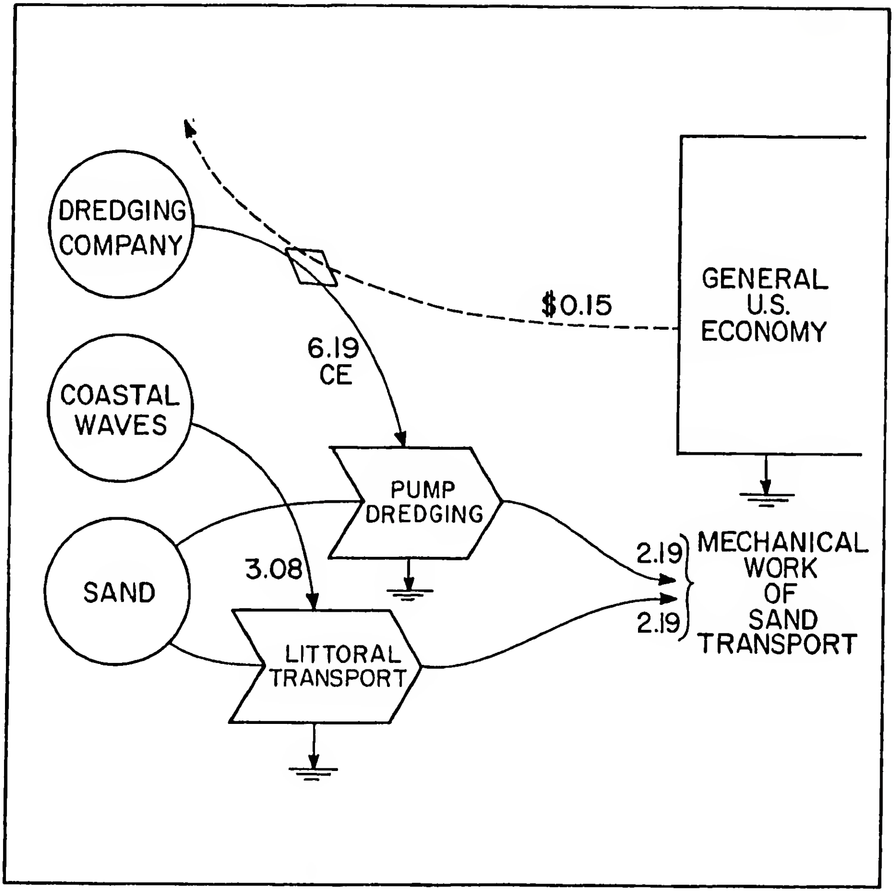

(b)
Y=0.64+0.11 Ln X
r^2=0.78
Significant
Y
X
RATIO, SAND TRANSPORT WORK / WAVE ENERGY, E_A
0.0
0.5
1.0
1.5
10^{-1}
1.0
10
10^2
ALONGSHORE WAVE ENERGY, E_A, Kcal x10^9

called "economy of scales" by which larger projects with larger dollar investments yield greater economic efficiency than smaller projects. Therefore the ratio of alongshore-wave-energy (E_A) to mechanical work of sand transport was plotted in Fig. 53b against E_A, thus avoiding artifacts of economic scale to emphasize the relationship between quantity and quality of wave energy. Figure 53b indicates a significant logarithmic function (fitted to a logarithmic equation), where the ability of waves to do work (transport sand) per unit wave energy increased with increasing magnitude of wave energy, toward an asymptote.

For the purposes of this study the energy quality ratio for waves on the southern Atlantic coast of Florida was used. The mean ratio for Florida is 2.01 compared to 2.75 for all data given in Table 34. It suggests that a Calorie of alongshore wave energy can do about twice the work of a Carloie of coal. However, since coastal wave energies are most often referenced to mean breaker height, irrespective of direction of propagation, this energy quality ratio was also related to the scalar value of wave energy, as follows.

Walton (1973) has published wave height "roses" which give mean annual height and frequency of occurrence for several regions of the Florida coast. From this data the absolute value of the alongshore vector (E_A) was calculated and compared with the scalar value (E_o) of all waves directed at the Florida peninsula in this southern Atlantic coastal zone. The value of E_A was found to be 59% of E_o for this region. Therefore, the energy quality ratio for waves (scalar value) was estimated to be 2.01 (.59) = 1.19, or very nearly equivalent to coal. This data is graphically summarized in Fig. 54, which shows the costs (and equivalent energy) for producing 2.19×10^9 kcal of transport work

Figure 54. Diagram summarizing data to indicate the relative energy inputs required from coastal waves and from fossil fuel based dredging to accomplish the same sediment transport work. Energy values are given in kcal x 10^9 and money flows are in 1967 U.S. dollars x 10^6.


DREDGING COMPANY
COASTAL WAVES
SAND
GENERAL U.S. ECONOMY
$0.15
6.19 CE
PUMP DREDGING
3.08
LITTORAL TRANSPORT
2.19
2.19
MECHANICAL WORK OF SAND TRANSPORT

by dredging compared to the wave energy needed to accomplish the same work. It might be noted that the results of this elaborate calculation correspond nicely with the calculation of energy quality of hydrostatic head (1.7 CE) given by Boynton (1975). Thus, the quality of wave energy which has both kinetic and turbulent energetic components, is slightly lower than the quality of hydrostatic potential (equivalent to kinetic energy) as previously calculated.

Energy Quality of Tides

Data are assembled in Table 35 from various sources to show the relative moneys and energies involved in the construction and operation of two tidal driven electric power plants. The major economic and energetic processes involved in the operation of a tidal electric power plant are illustrated in Fig. 55. The plant at La Rance, France has been in operation since 1963, while the Bay of Fundy plant which has received intensive study periodically since its conception in the 1930's, remains undeveloped. In this section the net output from these plants (electricity minus annual costs) is compared to the tidal energy fueling the electric generation turbines.

Details of annual operating expenses expected for the Bay of Fundy plant were reported by Lawton (1972b), but were not available for the operational plant at La Rance. Annual costs were estimated, however, for the French facility by assuming that operating expenses would be proportional to the capital investment per kilowatt hour (KWH) of plant output. Annual costs were converted to equivalent coal energy units by using energy/dollar ratios for the U.S. economy given by Kylstra (1974) and for France as given by Darmstadter et al. (1971). According to

Table 35. Summary of data comparing tidal energies to net energy output from the electric power plant at La Rance, France and from a proposed plant on the Bay of Fundy, Maine.

Parameter	Foot-note	Operating Plant at La Rance	Proposed Plant on Bay of Fundy
Electric Generating Capac., MWe	1	240	2916
Electric Output, KWH x 10^9/yr	2	0.544	5.40
Output, kcal CE x 10^{12}/yr	3	1.68	16.72
Capital Investment, $ x 10^6 (1967)	4	93.3	603.2
Annual Costs Rate, $/KWH	5	0.0115	0.0075
Total Annual Costs, $ x 10^6/yr		6.26	40.50
Annual Costs, kcal CE x 10^{12}/yr	6	0.10	1.09
Cost of Storage $ x 10^6/yr	7	1.3	8.5
Cost of Storage, kcal CE x 10^{12}/yr	8	0.02	0.23
Net Energy Output, kcal CE x 10^{12}/yr		1.56	15.40
Tidal Amplitude, cm x 10^2	9	7.40	9.88
Area of Basins, cm^2 x 10^{12}	10	0.22	0.46
Tidal Energy, kcal CE x 10^{12}/yr	11	2.06	7.60
Ratio, Output (CE)/input		0.76	2.03

Table 35. (Continued)

1) From Lawton (1972a) and Mauboussin (1972).

2) Same as above.

3) La Rance: Output $= (0.544 \times 10^9 \text{ KWH/yr})(860 \text{ kcal/KWH})(3.6 \frac{\text{coal}}{\text{elec}})$ $= 1.68 \times 10^{12}$ kcal CE/yr

Bay of Fundy: Output $= (5.40 \times 10^9 \text{ KWH/yr})(3.6)$ $= 16.72 \times 10^{12}$ kcal CE/yr

4) From Lawton (1972b) and Anonymous (1966) corrected to 1967 U.S. dollars using BEBR (1974).

5) Annual costs rate including amortization of capital outlay and interest on loan = $\$53.6 \times 10^6$/yr for site 7.1, Bay of Fundy. This is \$0.0075/KWH generated. Assuming that annual expenses for the two projects are proportional to capital investment per KWH. Thus, for La Rance:

Annual rate = (\$0.0075/KWH)((93.3/0.544)/(603.2/5.4)) = 0.0115

6) Converted to energy value using 27,000 kcal/\$ for U.S. in 1967 (Kylstra, 1973) and a ratio of 15,400 kcal/\$ for French economy.

7) Cost to develop pumped-storage facility ancillary to tidal plant is estimated from data of Lawton (1972b) for Bay of Fundy. Size of plant = 10^6 KW; Capital expense = \$6.80/KW yr; Operation expense = 25% = \$1.70/KW yr;

Cost = $(10^6 \text{ KW})((6.8 + 1.7)\$/\text{KW yr}) = \$8.5 \times 10^6/\text{yr}$

Assume same percentage for La Rance.

8) Energy/\$ ratio for 1967 = 27,000 kcal/\$ in U.S. (Kylstra, 1974) and 15,400 kcal/\$ in France (Darmstadter et al., 1971)

Cost = $\$8.5 \times 10^6$/yr (27,000 kcal CE/\$) = 0.23×10^{12} kcal CE/yr.

9) Tidal range amplitude is RMS from Lawton (1972a) for Bay of Fundy, and from Anonymous (1966) for La Rance.

10) From same as above.

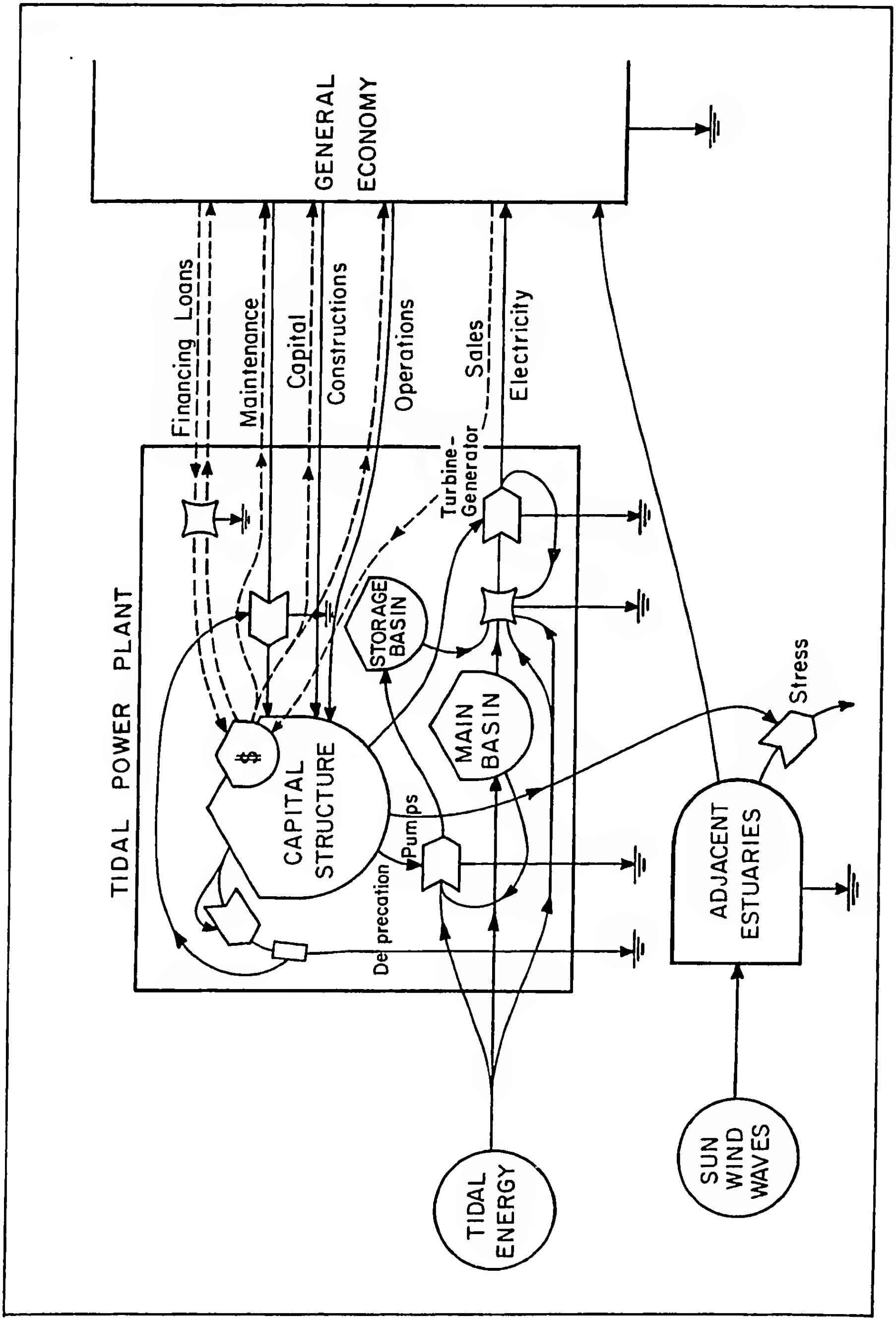
11) Tidal energy is calculated as the work of a pressure field = $1/2\ \rho g\ A\ h^2$, where A = basin area; h = tidal range; ρ = density of coastal water = 1.025 g/cm^3; g = acceleration of gravity = 980 cm/sec^2. Calculation assumes that tides do work moving material in and out of basin. Bay of Fundy:

$$\text{Tidal Energy} = \frac{1}{2}(1.025)(980)(0.46 \times 10^{12})(988)^2(705 \text{ cycles/yr}) = 3.80 \times 10^{12} \text{ kcal/yr}$$

La Rance:

$$\text{Tidal Energy} = \frac{1}{2}(1.025)(980)(0.22 \times 10^{12})(744)^2(705 \text{ cycles/yr}) = 1.08 \times 10^{12} \text{ kcal/yr.}$$

Figure 55. Major economic and energetic processes involved in construction and operation of tidal generated electric power plant.


TIDAL POWER PLANT
GENERAL ECONOMY
Financing Loans
Maintenance
Capital
Constructions
Operations
Sales
Electricity
Turbine-Generator
STORAGE BASIN
MAIN BASIN
$
CAPITAL STRUCTURE
Pumps
Deprecation
Stress
ADJACENT ESTUARIES
TIDAL ENERGY
SUN WIND WAVES

Darmstadter et al. (1971) the French economy is only 57% as energy intensive as the U.S. system. Electric output was multiplied by 3.6 to estimate its coal equivalent energy units.

The rate at which electric power is generated from these plants varies according to the tidal cycle. A number of schemes involving multiple basins are used to help damp-out the variable power plant output, but these are only moderately effective. The rate at which electricity is demanded by the economy is also periodic. However, more often than not, the generating cycle is out of phase with the tidal cycle which exhibits a daily precession of about 45 minutes. Coal-fired steam electric plants can tune their cycle to correspond to demand, but tidal plants cannot. Therefore, to make the electric output from tidal plants equivalent to that from coal-burning plants, the tidal plants must have provisions for power storage coupled to their operation. By storing during periods of excess power generation, demand can be met during groughs of the generating cycle. In this calculation the additional cost which is needed to operate a "pumped-storage" plant in conjunction with the tidal facility was estimated. The pumped-storage plant stores energy in the form of elevated water, which in turn can release its head through turbine-generators to recreate needed electricity. The annual costs for such a pumped-storage plant were calculated on the basis of data given in Lawton (1972b).

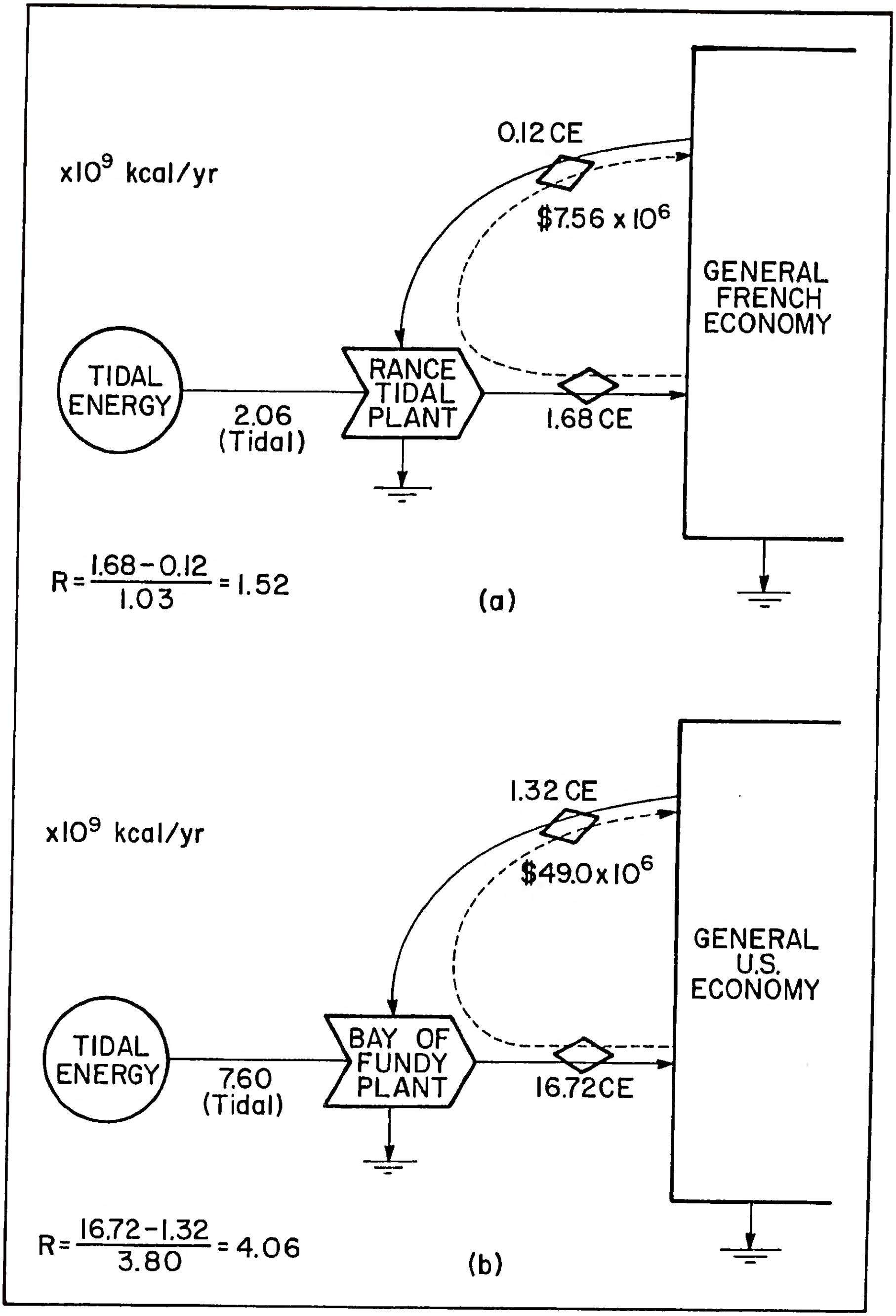
The potential energy of tides was calculated as the work of a pressure field created by the mass of elevated water. The calculation assumes that tidal energy has equal potential to do work in both flood and ebb phases. The energy of tides is a function of the square of the tidal amplitude so that a 34% increase in tidal range between the two case sites developes a 270% increase in potential energy (Table 35).

The ratio of net output from these power plants (expressed in coal equivalents) to input tidal energy is defined as the energy quality ratio for tides compared to coal. These data are summarized in Fig. 56. The quality of tidal energy is indicated as 2.7 times higher at Bay of Fundy site where the potential energy is 3.7 times higher than at La Rance. This is the same trend as found previously for waves, where increasing quality accompanies increasing quantity. However, two points by no means constitute a significant relationship, and the effect of "economy of dollar scale" may be exaggerating this effect, since the Bay of Fundy plant is proposed at an order of magnitude larger scale than La Rance. The direct application of this data to the study area on the Florida Gulf Coast is somewhat tenuous, since Florida tides generate about 2% as much energy per area as do Rance tides. Nevertheless, for lack of a more precise figure, the energy quality ratio calculated for tides at La Rance (1.5) was used for the purposes of this study.

Energy Quality of Freshwater's Chemical Potential

In this section data are compiled to examine the energy and economic flows in selected desalination plants throughout the world. These case studies, taken from various sources, were selected as being representative of the more cost-effective plants, i.e., those able to effect the greatest removal of salt at the lowest cost. This selected group is dominated by the distillation process. Generally, seawater distillation is considered an economically competitive means of producing freshwater in only the most arid and/or remote regions of the world (Kohout and Sachs, 1971). Therefore, these calculations investigated the value of

Figure 56. Diagram summarizing data to indicate the net output from tidal electric power plants compared to input energy of tides, (a) for operating plant at La Rance, France, (b) for proposed plant at Bay of Fundy, Maine. Energy values are given in kcal x 10^9 coal equivalents or tidal equivalents and money flows are in 1967 U.S. dollars.


x10⁹ kcal/yr
0.12 CE
$7.56 x 10⁶
GENERAL FRENCH ECONOMY
TIDAL ENERGY
RANCE TIDAL PLANT
2.06 (Tidal)
1.68 CE
R = (1.68 − 0.12) / 1.03 = 1.52
(a)
x10⁹ kcal/yr
1.32 CE
$49.0 x 10⁶
GENERAL U.S. ECONOMY
TIDAL ENERGY
BAY OF FUNDY PLANT
7.60 (Tidal)
16.72 CE
R = (16.72 − 1.32) / 3.80 = 4.06
(b)

water only for areas in which water is highly limited. The major processes involved in operation of a generalized desalination plant are summarized in Fig. 57.

The quality of freshwater's chemical "free energy" (ΔG) was estimated by comparing the energy involved in desalting with the chemical potential energy available in the clean water (H.T. Odum, 1970). This chemical energy difference between salt and fresh water has been termed by Spiegler (1962) as the "minimum energy" for splitting seawater into freshwater and brine. He suggested that the ratio of this figure to the fuel energy required for the "splitting" process indicates the process efficiency. However, this efficiency considers only direct fuel energy involved and not indirect energies in the form of goods and services.

Pertinent desalination data are provided in Table 36. Annual cost figures are given in U.S. Dollars of the particular year for which the data was reported, and are converted to coal equivalent energy using appropriate energy/dollar ratios specific to given country or region (Darmstadter et al., 1971; Kylstra, 1974). Feedwater and process water salinity data were not available for all cases. It was assumed for six of the plants that input and output salinities were 35,000 and 50 ppm, respectively, based on data for typical operating characteristics of multi-stage flash-distillation processes (United Nations, 1969) and on knowledge that the ocean served as source of input water.

The ratio of total energy cost for desalination (as inferred from dollar and fuel consumption figures) to the chemical potential free energy (ΔG) released in the process may be an indication of the energy quality ratio of fresh water as a dilutant. For the data provided in Table 36, this ratio varies from 1.2 to 6.1 with a mean of 3.1. This

Figure 57. Major economic and energetic processes involved in construction and operation of desalination plant.

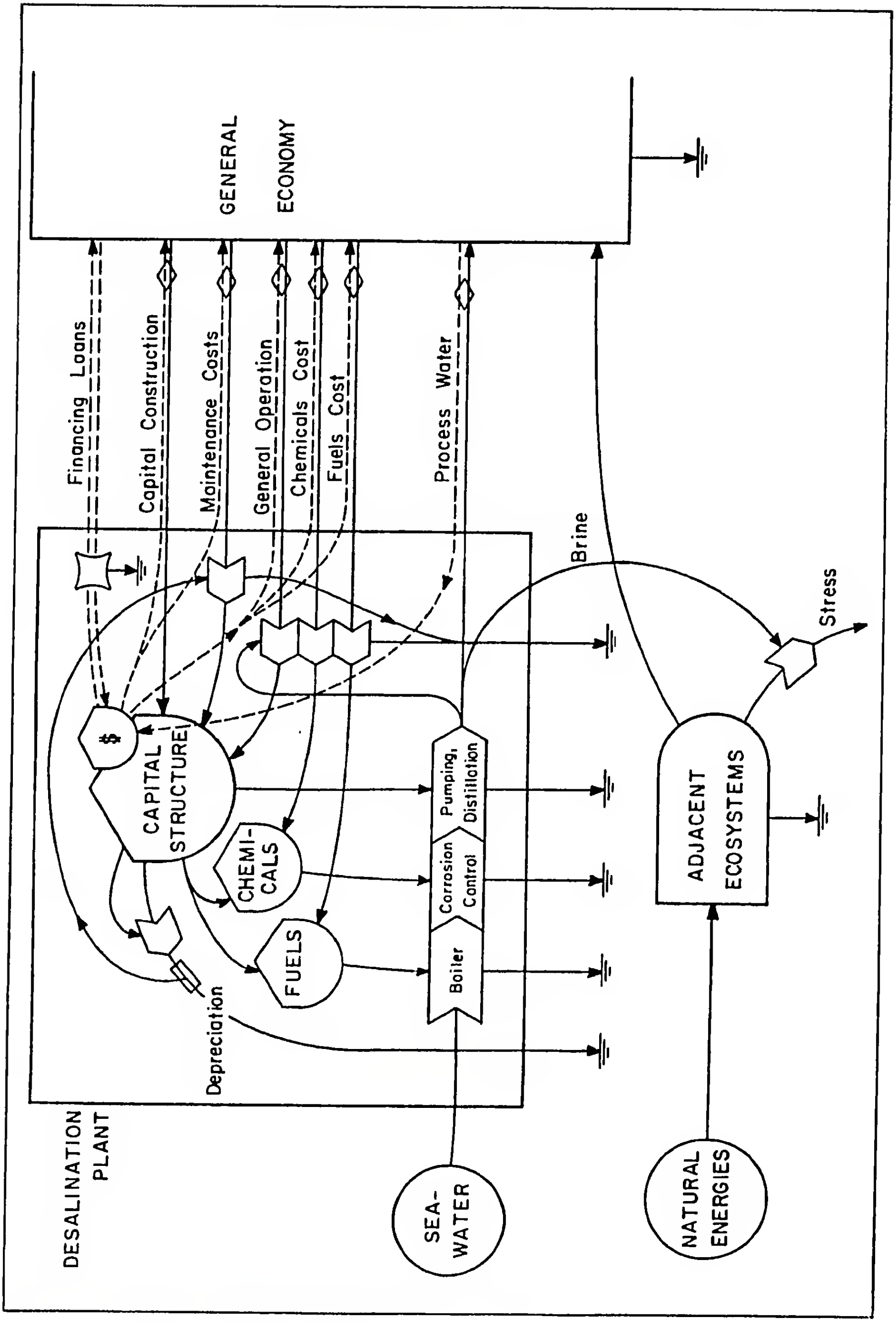

GENERAL
ECONOMY
Financing Loans
Capital Construction
Maintenance Costs
General Operation
Chemicals Cost
Fuels Cost
Process Water
Brine
Stress
$
CAPITAL
STRUCTURE
CHEMI-
CALS
FUELS
Pumping,
Distillation
Corrosion
Control
Boiler
Depreciation
ADJACENT
ECOSYSTEMS
DESALINATION
PLANT
SEA-
WATER
NATURAL
ENERGIES

Table 36. Summary of desalination data for selected, cost-effective plants.

Plant location	Method[a]	Capacity m^3/day	Annual cost minus direct energy[b]		Electric and fuel costs[c] kcal CE/m^3	Salinity, ppm[d]		Free energy[e] ΔG, kcal/m^3	Ratio, Annual cost/ Free energy
			\$/m^3	kcal CE/m^3		in	out		
Aruba[f]	ST	9000	.56	13,300	12,260	35,000	5	5,374	4.8
Isreal[f]	VF	908	.43	9,630	9,410	41,500	500	3,142	6.1
Iran[f]	MFD	1390	.51	9,080	11,170	35,000	25	4,395	4.6
Kuwait[f]	ST	4500	.43	8,340	9,410	45,000	50	5,302	3.3
Kuwait[f]	MFD	9000	.43	8,170	9,410	45,000	50	5,302	3.3
#44-49,20-24[g]	MFD	1045	.29	4,960	6,350	35,000	50	3,971	2.8
Saudi Arabia[h]	MFD	38,000	.14	2,180	3,060	35,000	50	3,971	1.3
Israel[i]	MFD-DP	400,000	.13	2,080	2,850	35,000	50	3,971	1.2
Key West[j]	MFD	10,300	.22	5,680	4,820	35,000	50	3,971	2.6
Tijuana[k]	MFD-DP	28,400	.17	3,890	3,720	35,000	50	3,971	1.9
Cuba[l]	MFD	4,740	.28	7,220	6,130	33,600	50	3,919	3.4
Virgin Is.[m]	MFD	8,500	.20	4,060	4,380	35,000	50	3,971	2.1
Means				6,549	6,914			4,271	3.1

Table 36. (Continued)

[a] Abbreviations for methods are ST = submerged tube distillation; VF = vacuum freeze; MFD = multi-flash distillation; MFD-DP = multi-flash distillation combined with steam electric power plant in dual purpose unit.

[b] Annual costs are given in U.S. dollars of year reported (1959-1969), and energy costs are given in coal equivalents for the given year, estimated using kcal/$ ratios for particular country as reported by Darmstadter et al. (1971) and Kylstra (1974).

[c] Electricity and fuel costs taken as 6% and 7% of total cost, respectively (United Nations, 1964). Coal-equivalent energy per unit price taken from Zucchetto (1975a).

[d] Salinity values for most plants tabulated were reported in the literature. However, some are estimated based on knowledge that feedwater is ocean quality and on typical performance reported for particular method.

[e] Free energy of chemical potential is calculated from, $= nRT \ln (C_1/C_2) M_S$, where n = moles salt, R = gas constant, T = absolute temperature, M_S = mass of removed, C_1 = input salinity, C_2 = output salinity.

[f] United Nations (1964) $\Delta G = (\frac{\text{mole}}{35\ \text{g}})(1.99 \times 10^{-3}\ \text{kcal/deg·mole})(305°)(10^6\ \text{g/m}^3)(\frac{C_1}{1000-(C_1 - C_2)}) \ln (C_1/C_2)$.

[g] Location of plants not given (United Nations, 1969). A composite energy/$ ratio is used assuming all are located in Caribbean and Near East.

[h] Siefert et al. (1973). [i] Clawson et al. (1969). [j] Wright (1969). [k] Steinbruchel and Beagle (1968).

[l] Jebens and Dykstra (1965). [m] Foster (1969).

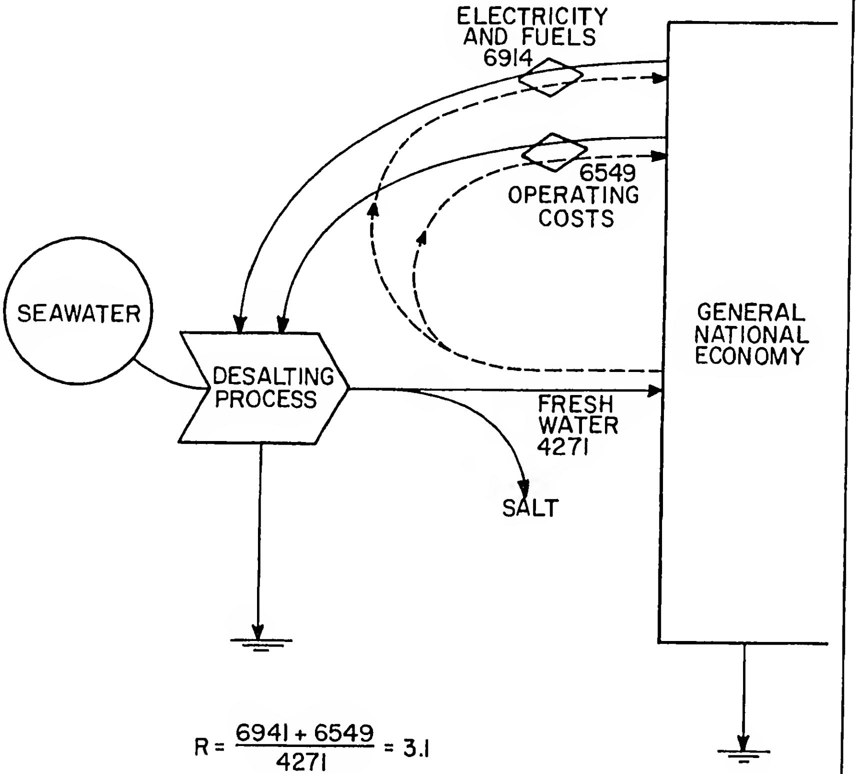
indicates that the ΔG may be higher energy quality than coal. Figure 58 illustrates the general interactions involved in desalinization.

Energy Quality of Estuarine Animals

In this section, a detailed model was developed to show the quantitative trophic relationships between organisms in an estuarine ecosystem. This model was used to determine the relative importance of these organisms within their ecosystem and the energy cost (in terms of gross primary productivity) to support them. Mean annual values of stocks and flows of organic matter for major components in a saltmarsh creek ecosystem near Crystal River are summarized in Table 37. Feeding relationships indicated in Table 37 are illustrated in the trophic web model of Fig. 59. The model was generally organized with increasing trophic level from left to right. This diagram emphasizes the almost overwhelming trophic complexity in the saltmarsh creek ecosystem. Even with numerical values attached to such a diagram, there was no clear way to relate the production of higher level organisms quantitatively to primary production. In addition, the ultimate purpose, here, was to develop general trophic relationships, which were relevant not only to this particular ecosystem, but also relevant to other estuarine systems at Crystal River. Therefore, a general trophic-function model was developed for the creek ecosystem, with four secondary trophic levels along each of two distinct branches (Fig. 60).

Measurements of standing stocks used here were all specific to the Crystal River ecosystems, with marsh grass and epiphyte data from Young (1974a, b); phytoplankton from Gibson (1975); zooplankton from

Figure 58. Diagrams summarizing the energy used in selected desalination plants compared to chemcial energy stored in the process. Numbers are given in kcal/m^3.



$$R = \frac{6941 + 6549}{4271} = 3.1$$

Table 37. Summary of mean annual values of stocks and flows of organic matter for major components in control salt marsh creek ecosystem. See Fig. 61.

Species or Grouping	Standing Stock, mg/m^2	Consumption, mg/m^2·day	Respiration, mg/m^2·day	Production, mg/m^2·day	Feces, mg/m^2·day	Food Habits	
						Food item	% Total Diet
Epiphytic algae	98.8	569.3	240.5	328.8			
Phytoplankton	300.0	453.3	113.3	340.0			
Spartina alterniflora cord grass	326,300	2992.1	706.6	2285.5			
Juncus roemarianus black rush	1,012,700	17.1×10^3	6260.0	10.9×10^3			
Detritus	694,600	5726.5	2833.9	2892.6			
Zooplankton, primarily *Acartia tonsa*	261.0	146.4	31.3	41.9	73.2	Detritus Phytoplankton	75[a] 25
Benthic micro-invertebrates, primarily polychoeta and nematoda	8220.0	1488.1	699.0	45.0	372.0	Detritus	100[b]

Table 37. (Continued)

Species or Grouping	Standing Stock, mg/m^2	Consumption, mg/m^2·day	Respiration, mg/m^2·day	Production, mg/m^2·day	Feces, mg/m^2·day	Food Habits	
						Food item	% Total Diet
Benthic macroinvertebrates, primarily *Uca pugnax*	5890.0	629.8	282.6	32.3	314.9	Detritus	100^c
Callinectes sapidus blue crab	38.0	1.74	0.95	0.32	0.47	Benthic inv. Detritus Fish Plant mat.	56.8^d 19.8 19.4 3.9
Carcharhinus limbutus blacktip shark	107.0	2.51	0.80	1.21	0.50	*Mugil* sp.	100^e
Dasyatis sabina Atlantic stingray	40.0	0.72	0.46	0.12	0.15	*M. beryllina* *Mugil* sp. *F. grandis* *C. variegatus* *F. carpio*	70.4^e 11.5 10.3 3.5 1.7
Anchoa hepsetus striped anchovy	4.0	0.16	0.11	0.02	0.03	Assumed same as below	

Table 37. (Continued)

Species or Grouping	Standing Stock, mg/m2	Consumption, mg/m^2·day	Respiration, mg/m^2·day	Production, mg/m^2·day	Feces, mg/m^2·day	Food Habits	
						Food item	% Total Diet
A. mitchilli bay anchovy	15.0	1.11	0.73	0.16	0.22	zooplankton	58.0[f]
						detritus	33.0
						benthic inv.	9.0
Strongylura sp., marina and notata Needlefish	46.0	1.57	0.89	0.36	0.32	A. mitchilli	39.9[e,j]
						M. beryllina	39.7
						Benthic inv.	7.7
						L. rhomboides	4.1
						F. similis	3.0
						Mugil sp.	2.2
						Breveortia sp.	1.5
						E. argenteus	1.4
						Strongylura sp.	0.3
						F. carpio	0.2
						Microgobius sp.	0.2
Cyprinodon variegatus Sheedpshead Killfish	16.0	1.39	0.54	0.20	0.65	Detritus	57.0[g]
						Plant mat.	32.0
						Benthic inv.	11.0

Table 37. (Continued)

Species or Grouping	Standing Stock, mg/m^2	Consumption, mg/m^2·day	Respiration, mg/m^2·day	Production, mg/m^2·day	Feces, mg/m^2·day	Food Habits	
						Food item	% Total Diet
Floridichthys carpio Fold-spotted Killifish	27.0	1.86	0.89	0.29	0.68	Detritus	38.0[g]
						Benthic inv.	33.0
						Plant mat.	17.0
						Zooplankton	12.0
Fundulus grandis Gulf Killifish	156.0	6.58	3.70	1.56	1.32	Benthic inv.	40.7[e]
						M. beryllina	40.6
						A. mitchilli	7.6
						E. argenteus	5.6
						F. carpio	1.4
						P. latipinna	1.4
						Mugil sp.	1.2
						Shrimp	1.0
						F. similis	0.4
						C. variegatus	0.2
Fundulus similis Long-nosed Killifish	121.0	5.28	2.87	1.36	1.06	Benthic inv.	100.0[h]
Meridia beryllina Tidewater silverside	246.0	15.42	9.64	2.41	3.38	Benthic inv.	55.7[j,f,g]
						Zooplankton	38.0
						Detritus	6.3

Table 37. (Continued)

Species or Grouping	Standing Stock, mg/m^2	Consumption, mg/m^2·day	Respiration, mg/m^2·day	Production, mg/m^2·day	Feces, mg/m^2·day	Food Habits	
						Food item	% Total Diet
Eucinostomus argenteus Spotfin mojarra	82.0	6.30	2.94	1.84	1.53	Zooplankton	50.0^{g}
						Benthic inv.	36.0
						Detritus	14.0
Eucinostamus gula Silver jenny	2.0	0.13	0.06	0.04	0.03	Benthic inv.	$49.0^{g,j}$
						Zooplankton	39.0
						Detritus	12.0
Archosargus probatocephelus Sheepshead	13.0	0.31	0.12	0.08	0.11	Algae	50.0^{e}
						Benthic inv.	50.0
Lagodon rhomboides Pinfish	54.0	2.05	1.16	0.48	0.41	*A. mitchilli*	$36.2^{e,j}$
						M. beryllina	27.2
						Benthic inv.	25.8
						F. carpio	4.7
						M. gulosus	2.3
						Shrimp	1.2
						Strongylura sp.	0.9
						E. argenteus	0.4
						C. variegatus	0.3

Table 37. (Continued)

Species or Grouping	Standing Stock, mg/m2	Consumption, $mg/m^2 \cdot day$	Respiration, $mg/m^2 \cdot day$	Production, $mg/m^2 \cdot day$	Feces, $mg/m^2 \cdot day$	Food Habits	
						Food item	% Total Diet
Mugil cephalus Striped Mullet	727	22.38	8.32	2.87	11.19	Detritus Plant mat.	75.0[g] 25.0
M. curema White Mullet	23	0.84	0.28	0.14	0.42	Assumed same as above	
M. trichodon Silver Mullet	114	9.36	2.55	2.13	4.68	Assumed same as above	
Paralichthys albigutta Gulf Flounder	2	0.11	0.05	0.04	0.02	*E. argenteus* *L. rhomboides* *A. mitchilli* *M. beryllina* Benthic inv.	32.7[e] 29.0 19.0 18.2 1.1

[a] Estimated after Gillespie (1971). [b] Day et al. (1973). [c] Teal (1958). [d] Tagatz (1968).

[e] Homer (1976). [f] Darnell (1958), for juvenile fish. [g] W.E. Odum (1970) and Odum and Heald (1972).

[h] Cherr (1974). [i] Bolch et al. (1972). [j] Carr and Adams (1973).

[k] Consumption estimated from stomach analysis and from rations found in literature. See text for further explanation.

[l] Production for fish estimated from Homer (1974, 1976), for invertebrates from Evink and Green (1974) and from Alden (1976).

Figure 59. Energy diagram indicating web of trophic relationships in saltmarsh creek ecosystem at Crystal River. Feedbacks and other control pathways omitted. All relationships in figure are consistent with Table 37, except the diet of the black-tip shark which was inferred from "gut" analysis of three sharks taken in the power plant canals.

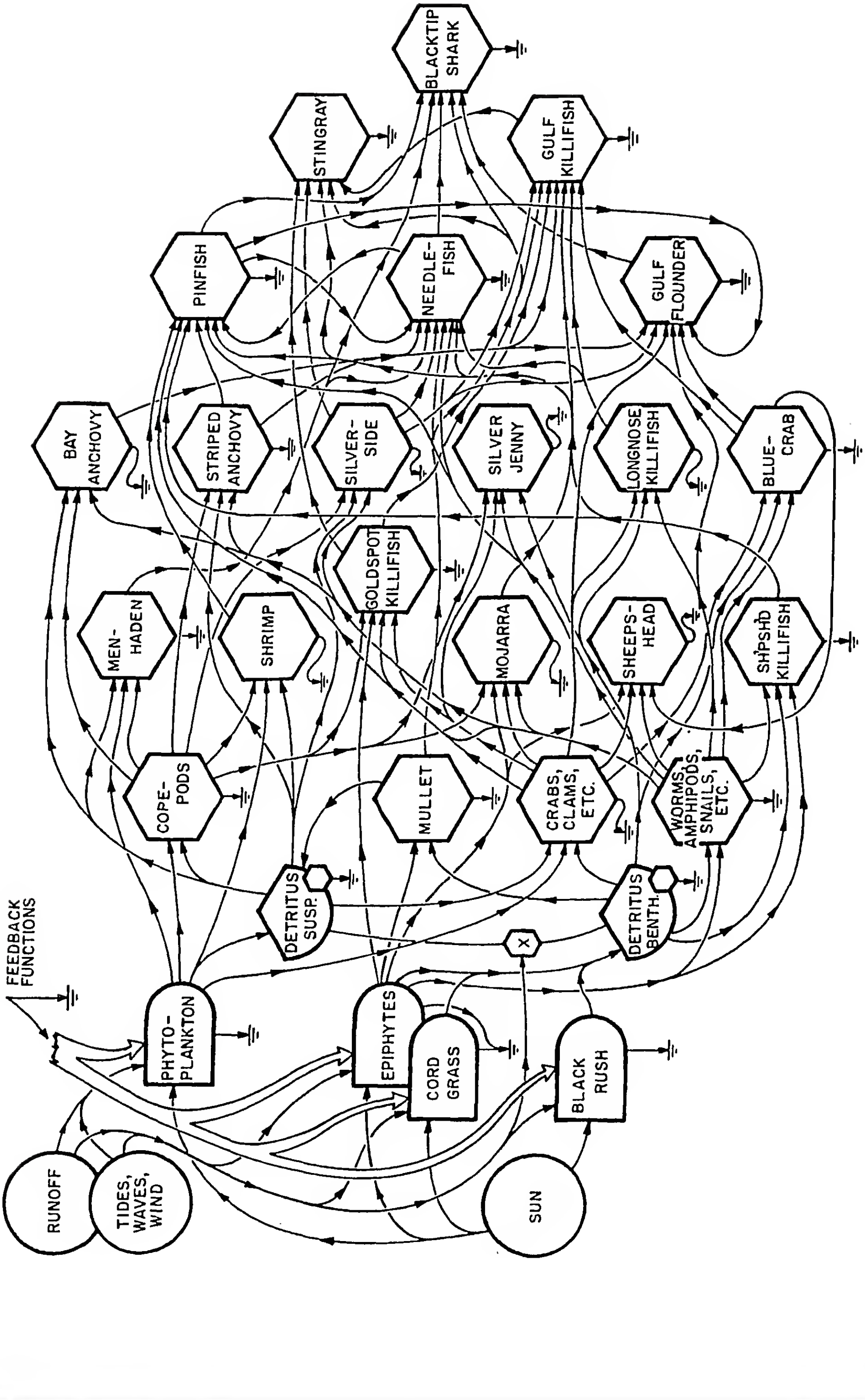

RUNOFF
TIDES, WAVES, WIND
SUN
FEEDBACK FUNCTIONS
PHYTO-PLANKTON
EPIPHYTES
CORD GRASS
BLACK RUSH
DETRITUS SUSP.
DETRITUS BENTH.
X
COPE-PODS
MULLET
CRABS, CLAMS, ETC.
WORMS, AMPHIPODS, SNAILS, ETC.
MEN-HADEN
SHRIMP
GOLDSPOT KILLIFISH
MOJARRA
SHEEPS-HEAD
SHPSHD KILLIFISH
BAY ANCHOVY
STRIPED ANCHOVY
SILVER-SIDE
SILVER JENNY
LONGNOSE KILLIFISH
BLUE-CRAB
PINFISH
NEEDLE-FISH
GULF FLOUNDER
STINGRAY
GULF KILLIFISH
BLACKTIP SHARK

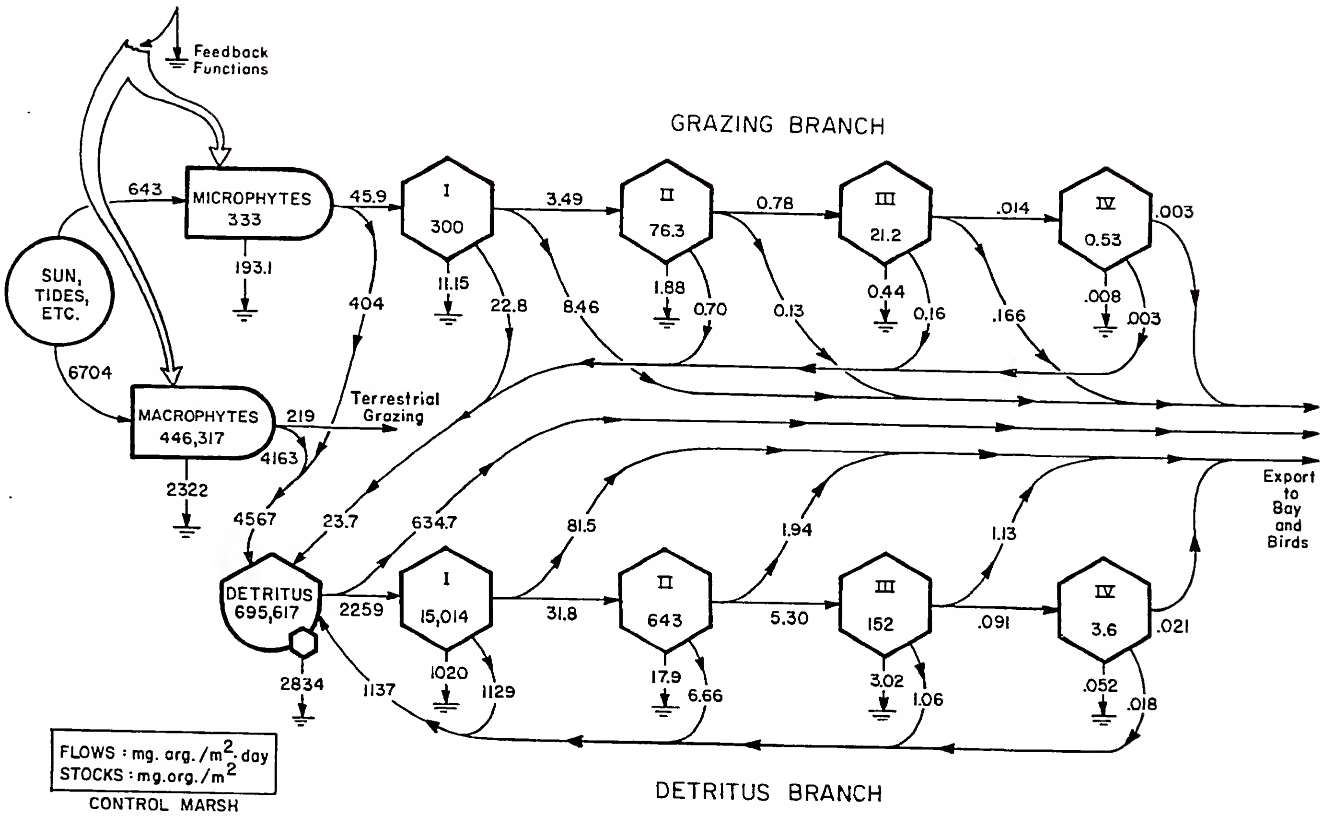
Figure 60. Generalized energy diagram depicting relationships between functional trophic groups in saltmarsh creek ecosystem at Crystal River. Groups are:

Grazing Branch

- I - Herbivores
- II - First Carnivores
- III - Second Carnivores
- IV - Third Carnivores

Detritus Branch

- I - Detritivores
- II - First Carnivores
- III - Second Carnivores
- IV - Third Carnivores


Feedback Functions
GRAZING BRANCH
SUN, TIDES, ETC.
643
6704
MICROPHYTES 333
193.1
MACROPHYTES 446,317
2322
219
Terrestrial Grazing
4163
45.9
404
4567
I 300
11.15
22.8
3.49
8.46
II 76.3
1.88
0.70
0.78
0.13
III 21.2
0.44
0.16
.014
.166
IV 0.53
.008
.003
.003
DETRITUS 695,617
2834
23.7
634.7
2259
1137
I 15,014
1020
1129
31.8
81.5
II 643
17.9
6.66
5.30
1.94
III 152
3.02
1.06
.091
1.13
IV 3.6
.052
.018
.021
Export to Bay and Birds
DETRITUS BRANCH
FLOWS : mg. org. /m2. day
STOCKS : mg.org./m2
CONTROL MARSH

Maturo et al. (1974); detritus from Gibson (1975) and Cottrell (1974); microinvertebrates from Evink and Green (1974); and macroinvertebrates and nekton from Homer (1976). Information on food habits of nekton was derived from stomach analysis by Homer (1976), Carr and Adams (1973), and Bolch et al. (1972) and Appendix C (this study) for Crystal River, amended with data from other studies in Florida and the Gulf Coast. Ontogenic changes in an organism's feeding habits were taken into account whenever possible by correlating size class and feeding data (Carr and Adams, 1973). Feeding relationships for other organisms at lower trophic levels were assumed less complex and were taken from various sources (MacGinitie and MacGinitie, 1968; Newell, 1970, Odum and Heald, 1972; Darnell, 1958; Green, 1968). Some values for fish respiration were taken from Crystal River studies (Homer and Kemp, 1976) and from Nicol (1967). Production values were calculated from Homer (1974), Alden (1976) and Evink and Green (1974). Consumption and assimilation rates were inferred from the work of Mann (1965), Warren and Davis (1967), Pandian (1967) and MacKinnon (1972), as well as Winberg (1956) and Nicol (1967).

The generalized trophic model is characterized by a bifurcated chain distinguishing between detritus (saprophage) and grazing (biophage) branches as has been suggested by E.P. Odum (1962), W.E. Odum (1970) and Wiegert and Owens (1971). This diagram was derived from the detailed model (Fig. 59) in conjunction with data given in Table 37, by apportioning the diet of each organism in Fig. 61 into the distinct trophic categories illustrated (Fig. 62). This apportionment was done according to the specific fractions of an organism's diet which could be followed back to primary production through a number of steps (which correspond to a particular trophic level number of Fig. 60). Thus, a pathway with three steps along grazing branch would indicate third level (second carnivore), grazing. That portion of a given organism's total diet which could be followed along this pathway was used to apportion the organism's biomass and metabolic flows to this trophic level (second carnivore grazing branch).

Some of the data used to transform the specific arrangement of Fig. 1 into the general form of Fig. 60, are given in Appendix G. In Table G1 the detailed calculations are shown (as a methodologic example) for partial feeding coefficients of each species which function as first carnivores in the detritus branch. The stocks and flows apportioned from these species to that trophic function are also given. Table G2 summarizes all the partial-feeding coefficients for all organisms which were calculated as above and which were used to derive Fig. 60 from Fig. 59.

Energy quality ratios calculated for the generalized trophic functions of Fig. 60 are given in Table 38. Notice that the metabolic energy flows of an organism operating solely as a top carnivore on the detritus food chain would be over 60 times as high a quality as that of the fossil fuel, coal. Energy qualities for comparable carnivores on the detritus branch are more than 10 times higher than for the grazing food chain. It can be seen from Fig. 60 that about 10 times as much energy is shunted down the detritus branch, and that there is an additional grophis level along this chain (detritivore). Upgrade ratios (see Table G1) in Table 38 were generally about 3.5 for all carnivores and 2.0 for herbivores. Detritivores contributed an order-of-magnitude upgrade to account for the difference in energy qualities on the two branches.

Table 38. Energy quality ratios for various trophic levels in a food web for an estuarine ecosystem on the Gulf Coast of Florida.[a]

Trophic Position			
Branch	Level	Upgrade Ratio[b]	Energy Quality Ratio[c]
Grazing	Plant	1.4	0.07
	Herbivore	1.9	0.14
	First Carnivore	3.1	0.42
	Second Carnivore	3.4	1.44
	Third Carnivore	3.7	5.27
Detritus	Plant	1.5	0.08
	Detritus	2.0	0.15
	Detritivore	10.0	1.50
	First Carnivore	3.5	5.22
	Second Carnivore	3.5	18.17
	Third Carnivore	3.5	63.23

[a] Detailed trophic data analysis and calculation methods are given in Kemp et al. (1974) and Homer and Kemp (1976).

[b] Defined as (input/output) or (consumption/production) for each trophic level.

[c] Energy quality ratio compared to gross primary production is defined as amount of primary production needed to sustain unit amount of secondary production at given trophic level. Numbers given are relative to coal equivalent energy, which is about 20 times higher quality than gross primary production (Odum et al., 1975).

The trophic habits and partial-feeding coefficients (see Eq. (24)) for all species whose energy value was considered in this study, are given in Table 39. The energy quality ratios for particular organisms in this table were calculated by multiplying the partial-feeding coefficients for given trophic level (as indicated in the table) times the energy quality ratio for that trophic elvel (Table 38). This is the exact reverse of the original process of aggregating the food web model into a generalized model of trophic functions. Now, the trophic function energy qualities can be used to calculate energy quality ratios for any organism from a similar ecosystem. Thus, for example, it can be seen in Table 39 that Spot (Leistomus sp.) serve the following trophic functions: 20% detritivore; 24% first carnivore, grazing; 46% first carnivore, detritus; 10% second carnivore, detritus. Their energy quality ratio would then be = (.20)(1.5) + (.24)(.42) + (.46)(5.22) + (.10)(18.17) = 4.62. This indicates that a Calorie of production by Leiostomus sp. is equivalent to about 4.6 Calories of coal.

Table 39. General trophic habits of organisms considered in energetic analysis of Crystal River power plant and its effects on nearby estuary.

Organism Genus, Common Name	Diet,[a] food (fraction of total)	Partial-Feeding Coefficient[b] Trophic level (fraction of total)
Leiostomus, spot[f]	Zoop(.1);Inv(.6);Shr(.1);Detr(.2)	Dev(.2);FCG(.24);FCD(.46);SCD(.10)
Anchoa, Anchovie[c,e]	Zoop(.54);Detr(.22);Inv(.24)	Dev(.22);FCG(.29);FCD(.41);SCD(.08)
Gobiosoma, Goby[e,f]	Inv(.8);Detr(.2)	Dev(.2);FCG(.24);FCD(.48);SCD(.08)
Menidia, Silverside[c,d,e]	Zoop(.4);Detr(.05);Inv(.55)	Dev(.05);FCG(.33);FCD(.53);SCD(.09)
Sygnathus, Pipefish[i]	Zoop(.6);Inv(.3);Fish(.1)	FCG(.33);FCD(.48);SCD(.14);SCG(.05)
Bairdiella, Silver Perch[g]	Inv(.2);Shr(.5);Fish(.3)	FCG(.2);FCD(.2);SCD(.3);SCG(.2);TCD(.05);TCG(.05)
Opisthonema, Atl. Thread Herring[g]	Detr(.25);Inv(.25);Zoop(.5)	Dev(.25);FCD(.4);FCG(.27);SCD(.08)
Prionotus, Bighead Searobin[f]	Inv(.8);Shr(.2)	FCG(.28);FCD(.58);SCD(.11);SCG(.03)
Peneus, Shrimp[e]	Detr(.48);Alg(.2);Zoop(.1);Inv(.22)	Dev(.48);Herb(.2);FCG(.10);FCD(.22)

Table 39. (Continued)

Organism Genus, Common Name	Diet,[a] food (fraction of total)	Partial-Feeding Coefficient[b] Trophic level (fraction of total)
Polydactylus, Atl. Threadfin[m]	Detr(.25);Inv(.5);Zoop(.25)	Dev(.25);FCG(.22);FCD(.45);SCD(.08)
Ogcocephalus, Polkadot Batfish[m]	Inv(.6);Shr(.2);Crab(.2)	FCG(.22);FCD(.51);SCD(.17);SCG(.05);TCD(.05)
Chilomycterus, Striped Burrfish[l,m]	Inv(.6);Shr(.2);Crab(.2)	FCG(.22);FCD(.51);SCD(.17);SCG(.05);TCD(.05)
Lactophyrus, Scrawled Cowfish[m]	Inv(.6);Shr(.2);Ceb(.2)	FCG(.22);FCD(.51);SCD(.17);SCG(.05);TCD(.05)
Lagodon, Pinfish[d]	A. Mitchelli(.67);Inv(.26);Shr(.07)	FCD(.34);FCG(.08);SCD(.33);SCG(.19);TCD(.06)
Eucinostomus, Silver Jenny[e]	Inv(.49);Zoop(.39);Detr(.12)	Dev(.12);FCD(.49);FCG(.3);SCD(.09)
Harengula, Scaled Sardines[e]	Zoop(.8);Inv(.2)	FCD(.52);FCG(.38);SCD(.1)
Caranx, Crevalle Jack[k]	Menidia(.8);Shr(.2)	FCD(.14);SCD(.48);SCG(.3);TCD(.08)
Mugil, Striped Mullet[e]	Detr(.75);Algae(.25)	Dev(.75);Herb(.25)
Loligo, Squid[m]	Shr(.4);Fish(.6)	FCD(.19);FCG(.08);SCD(.39);SCG(.22);TCD(.12)

Table 39. (Continued)

Organims Genus, Common Name	Diet,[a] food (fraction of total)	Partial-Feeding Coefficient[b] Trophic level (fraction of total)
Calinectes, Blue Crab[e]	Inv(.57);Detr(.24);Fish(.19)	Dev(.24);FCD(.35);FCG(.15);SCD(.20);SCG(.06)
Ascidiacea, Tunicates[m]	Detr(.5);Algae(.13);Zoop(.2)	Dev(.15);Herb(.3);FCD(.1);FCG(.08);SCD(.02)

[a] Partial-Feeding Coefficient explained in Eq. (24).
Abbreviations for food types: Detr = detritus; Inv = benthic invertebrate; Shr = shrimp; Zoop = zooplankton.
Assume trophic functions of following: Zoop = Dev(.5);Herb(.4);, and Inv = Dev(.6);Herb(.3);FCD(.1).

[b] Refers to generalized categories of trophic habit or partial feeding coefficient, A (see Fig. 13b).
Abbreviation for trophic levels: Dev = detritivore; Herb = herbivore; FCG = first carnivore, grazing;
SCG = second carnivore, grazing; TCG = third carnivore, grazing; FCD = first carnivore, detritus;
SCD = second carnivore, detritus; TCD = third carnivore, detritus.

[c] Darnell (1958). [d] Homer (1974). [e] Odum and Heald (1972). [f] Moore and Posey (1973).

[g] Carr and Adams (1973). [h] Tagatz (1968). [k] Kemp (1977). [l] Bigelow and Schroeder (1953). [m] Estimate.

Simulation of Estuarine Ecosystem Model

Energy analyses given in the previous sections of this dissertation were extended to examine relationships between power plant and estuary which might develop under modified power plant conditions. Therefore, a computer model was developed to simulate estuarine ecosystems receiving waste discharges from an electric power plant. An energy diagram of this model is given in Fig. 61, with turbidity, inorganic nitrogen, plants, detritus, benthic invertebrates and nekton being the aggregated state variables defined for this system. Sunlight and heat (temperature) are the primary forcing functions for the model, but additional energy inputs include flows of silt, nitrogen, phytoplankton and seston (assuming constant rate of water exchange), as well as migrating fish. The differential equations describing the mathematical relationships between model components are given in Appendix F, Table F1. The rationale used in developing this model is described in Fig. 62 for each of the major state variables and connecting pathways of interaction. Sources of data for flows and storages of this model are given in Appendix F, Table F2, and computations of pathway coefficients are provided in Appendix F, Table F3. A print-out of the computer program for this model is also given in this appendix (Table F4).

Forcing Functions

In Fig. 63 input functions for the model are presented. Monthly mean values are taken from actual field measurements for 1973 and 1974, and thus some of the day-to-day variability is lost. However, because

Figure 61. Energy circuit diagram of estuarine ecosystem receiving waste discharges from power plant.

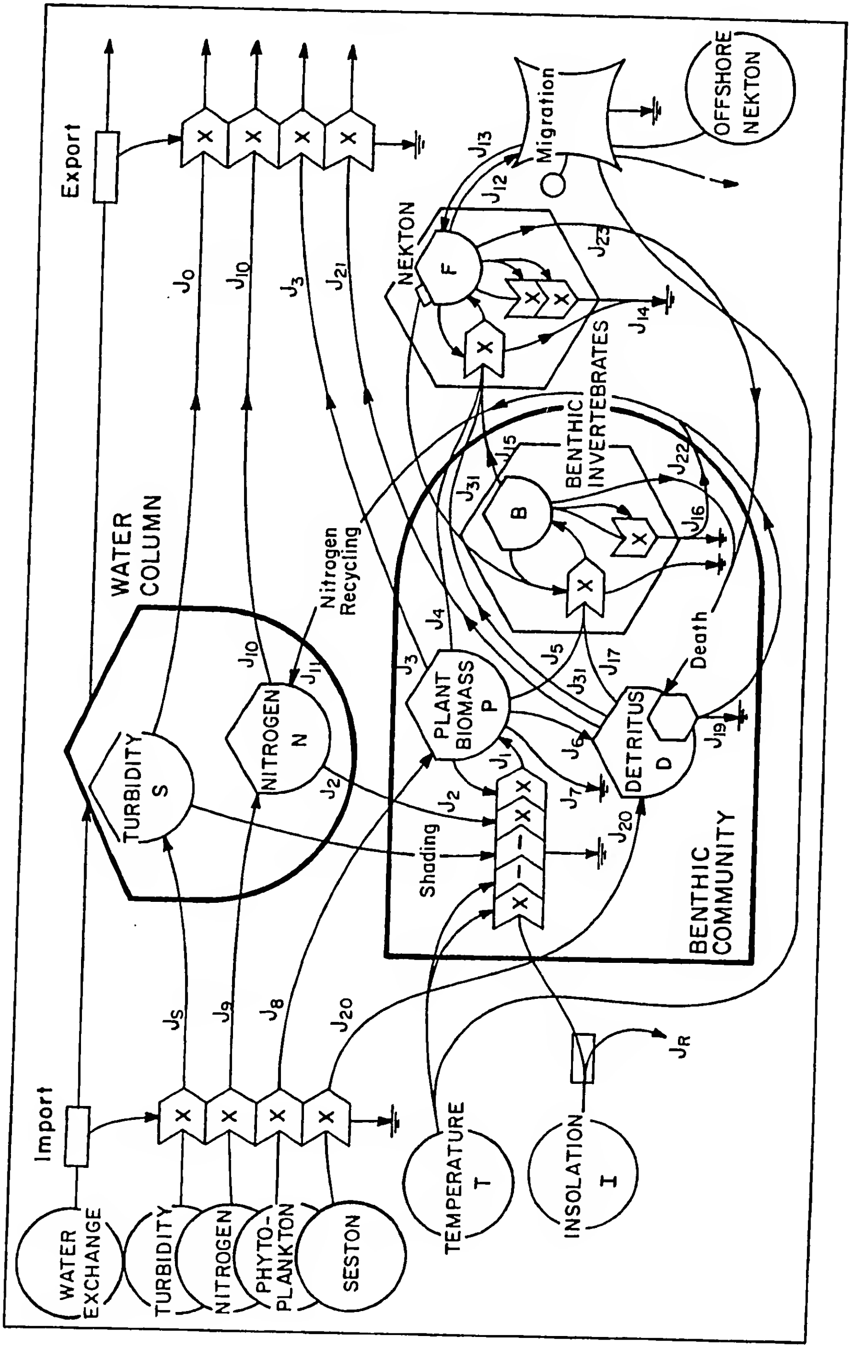
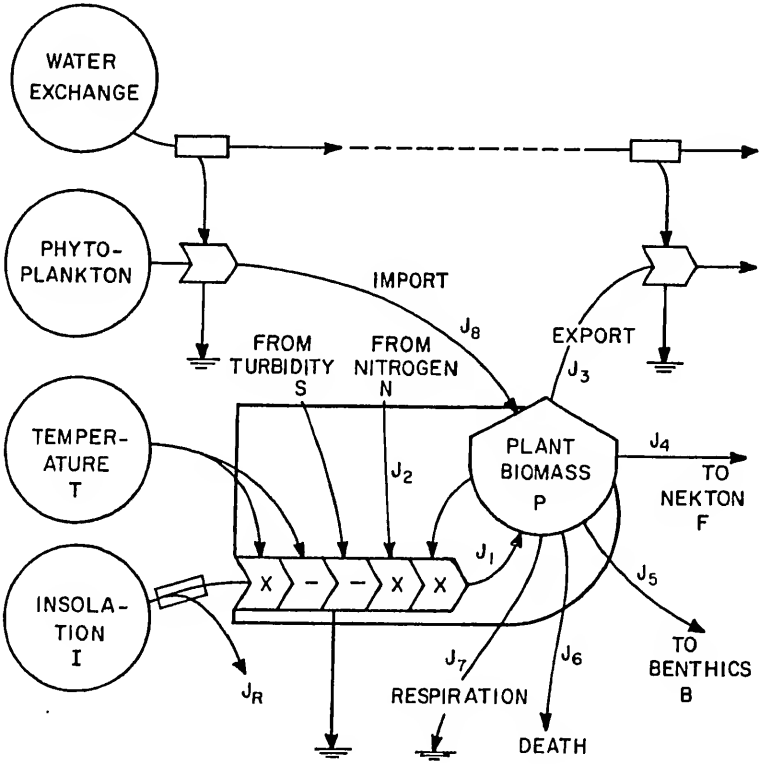

WATER EXCHANGE
TURBIDITY
NITROGEN
PHYTO-PLANKTON
SESTON
Import
Export
TEMPERATURE T
INSOLATION I
WATER COLUMN
TURBIDITY S
NITROGEN N
Nitrogen Recycling
Shading
PLANT BIOMASS P
DETRITUS D
Death
BENTHIC COMMUNITY
BENTHIC INVERTEBRATES
B
NEKTON
F
Migration
OFFSHORE NEKTON
X
J_0
J_1
J_2
J_3
J_4
J_5
J_6
J_7
J_8
J_9
J_{10}
J_{11}
J_{12}
J_{13}
J_{14}
J_{15}
J_{16}
J_{17}
J_{19}
J_{20}
J_{21}
J_{22}
J_{23}
J_{31}
J_S
J_R

Figure 62. Explanation of diagrammatic configurations and mathematical expressions used in conceptualizing the model of an estuarine ecosystem shown in Fig. 61.

(a) The autotrophic component of the ecosystem was included so as to define the basic energy input pathway, i.e., primary productivity, and because plant biomass constituted a significant portion of the total ecological structure (Van Tine, 1974). All plants are aggregated together into one state variable with characteristics closely akin to benthic plants only, because these bottom autotrophs comprised over 95% of the total plant biomass and up to 96% of the total productivity (Van Tine, 1974; Gibson, 1975; Smith, 1976). Primary production was modeled with a relatively complex equation which is similar to the Michaelis-Menten or Monod form (Wiegert, 1975) as derived from symbol configurations (McKellar, 1975; Kemp et al., 1977). The shading effects of turbidity which are best described with exponential decay (Patten, 1968) were approximated for a limited turbidity range by a linear, "drag" function (Williams, 1971). The output of this function (in the turbidity range used) never deviated from the exponential relationship by more than 15%. Temperature effects were modeled using a simplified version of the theoretical kinetic relationship proposed by Eyring and Eyring (1963). The derivation of this simplified form is given in Appendix E. Phytoplankton are imported and exported from this model with water exchanges (Rodgers et al., 1975). Respiration and death and excretion are approximated with linear, donor controlled drains, J_7 and J_6, respectively (Patten, 1975b). Grazing by nekton and benthics are both donor and receiver-controlled as reviewed by Odum (1972a).

Append., E



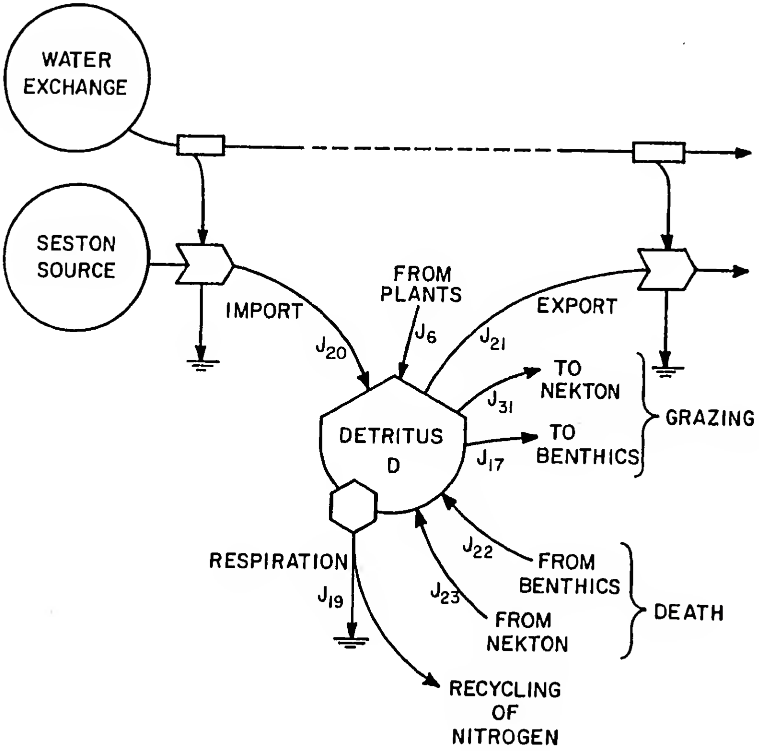
$$\dot{P} = k_1\ I\ (1 - k_D S)\left[T(1 - k_T(T - 10))\right] \frac{N \cdot P}{(1 + k_P N \cdot P)} +$$

$$J_8 - k_3 P - k_4 P \cdot N - k_5 P(k_B B + F) - k_6 P - k_7 P$$

Figure 62. (b) Previous work by Odum and Heald (1972) for the Southern Florida Gulf Coast, and more recently work by Homer and Kemp (1976) for Crystal River has indicated that detritus is the major source of food supporting these estuarine trophic webs. Detritus was thus considered as a state variable in this model. Included in this variable were both the particulate organic matter in the water column and the aerated organic stocks in the upper 1 mm of sediment (Kanwisher, 1962). It was assumed that only this aerated portion of the sediment was biologically active enough to be aggregated with the seston component(having similar time constants, O'Neill and Rust, 1976). It was further assumed that dynamics of the less active, anaerobic detritus would not be significant in two-year model simulations of trends. Import and export were effected by water exchanges (Rodgers et al., 1975). Death of organisms elsewhere in the model contributed to detritus stocks (J_6, J_{22}, J_{23}). Grazing by nekton and benthic invertebrates was again taken as an interaction with both donor and receiver control. Respiration was assumed to be a linear drain unaffected by temperature because of acclimitazation mechanisms at the ecosystem level (Bullock, 1955).

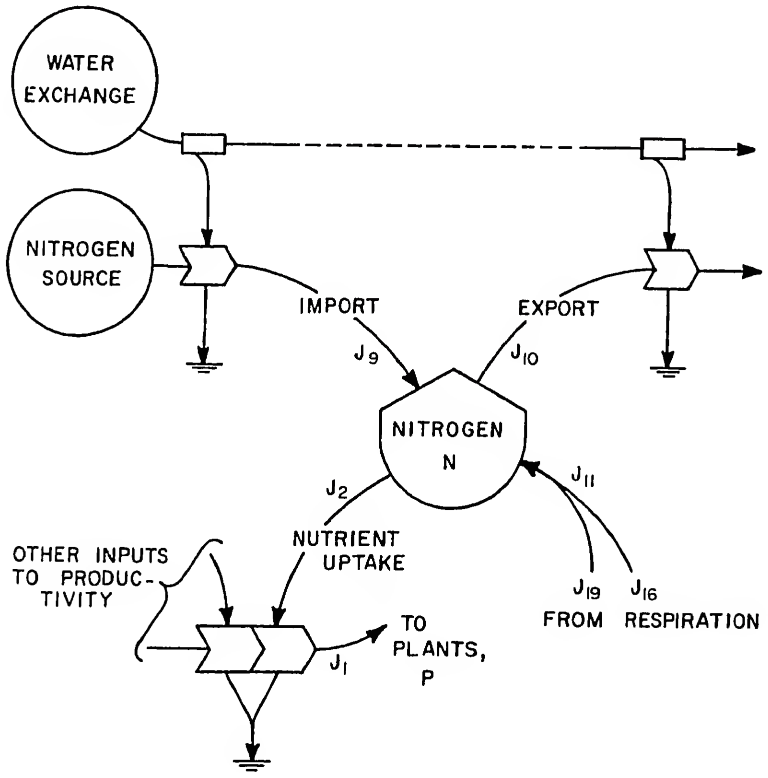
✓ [illegible]

anaerobic



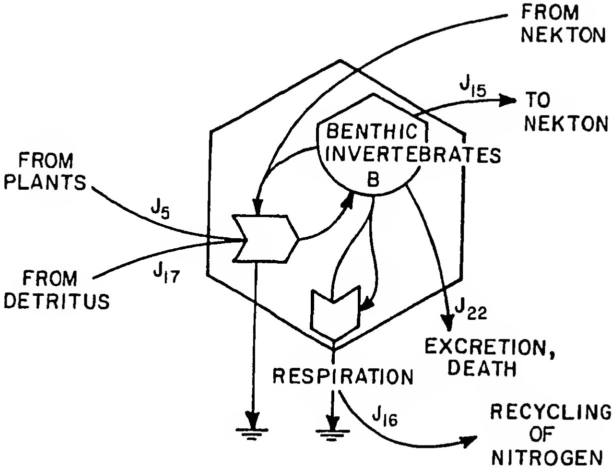
$$\dot{D} = J_{20} + k_6 P - k_{21} D - k_{17} D (k_B \cdot B + F) - k_{19} D + k_{22} B + k_{23} F - k_{31} D \cdot F$$

Figure 62. (c) Total inorganic nitrogen was selected as a state variable to include the general process of mineralization and cycling of nutrient materials. Nitrogen is probably the most limiting (least available) macronutrient at Crystal River based on relatively low concentrations in Florida waters (Odum, 1953) and on photosynthetic kinetic studies in coastal waters by Ryther (1971) and Putnam (1966a and b) on the North Florida Gulf Coast. At such low concentrations nitrogen uptake is likely to be the rate-limiting step in photosynthesis (Brezonik, 1972). Nitrogen is imported and exported with water exchanges (Rodgers et al., 1975). It is remineralized by microbial and animal excretion and respiration (Nicol, 1967). It is assumed that nitrogen is taken-up by plants during photosynthesis in proportion to the fractional nitrogen composition of plant biomass (E.P. Odum, 1971).



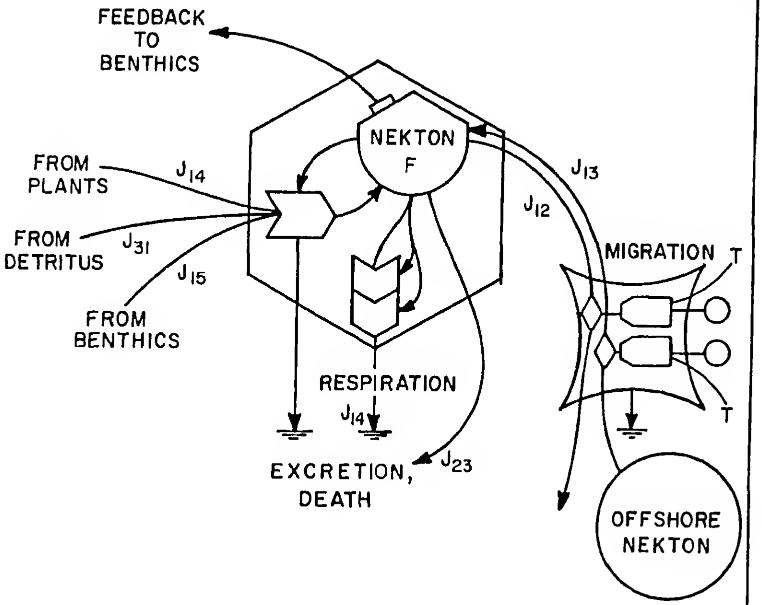
$$\dot{N} = -k_2(J_1) + J_9 + k_{11}(k_{19}D + k_{16}B^2) - k_{10}N$$

Figure 62. (d) Benthic invertebrates comprise a substantial portion of the ecosystem's total structure and metabolism (Smith, 1976; Evink and Green, 1974; Lehman, 1975) and were thus chosen as a state variable in this model. All benthic animals are aggregated together on the basis of similar characteristics of: habitat; general immobility; and trophic habits. Feeding was assumed to be a function of the food availability and an approtioned sum of the organisms doing the eating (B) and their predators (F) which serve to manage the benthic populations enchancing their metabolic efficiencies (Watt, 1968). An earlier equation used a simple multiplicative function of the three variables, but this gave unrealistic output, where severely reduced fish populations led to near-extinction of the benthics. Death and excretion were approximated by a linear drain (J_{22}), and predation by nekton was a combined donor/receiver-controlled function. Respiration was taken as the squared-power of the stocks, assuming density-dependent interactions (Odum, 1972), but is assumed independent of temperature due to acclimatization mechanisms at the organism and community levels (Bullock, 1955, 1958).



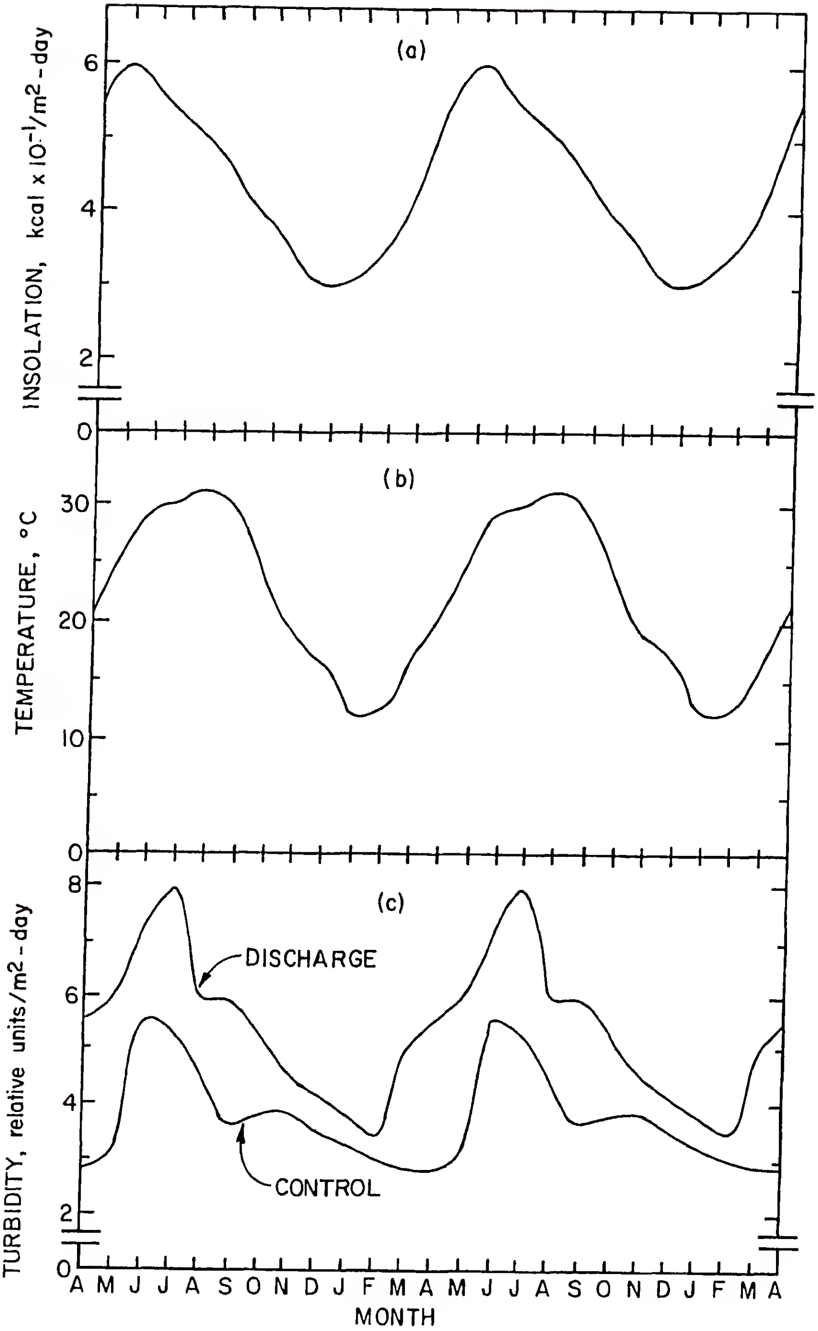
$$B = k_5 P(k_B B + F) + k_{17} D(k_B B + F) - k_{15} B \cdot F - k_{22} B - k_{16} B^2$$

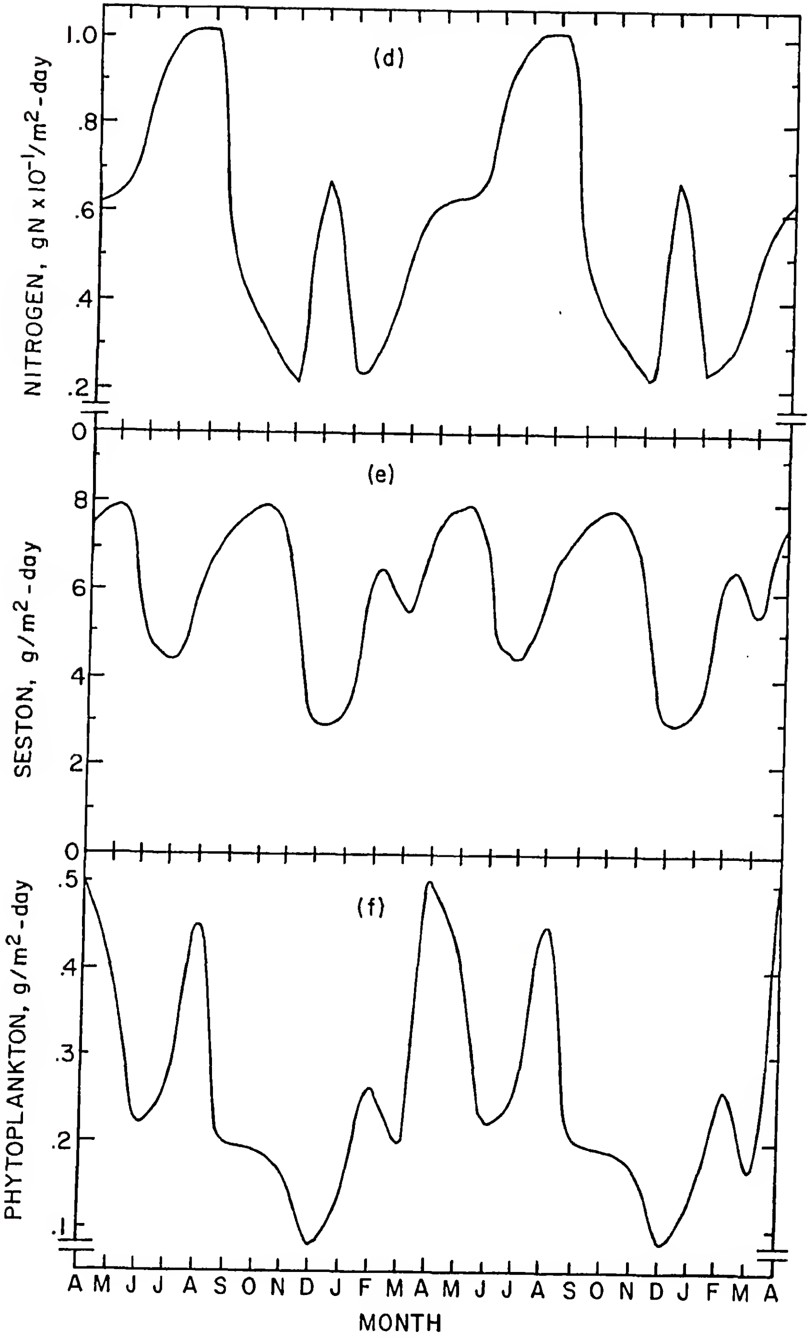
Figure 62. (e) The relatively large, mobile nekton are the major ecosystem managers in the estuary (H.T. Odum, 1971), and they were chosen as a state variable because of their importance in these roles. While the magnitude of their metabolic energies is relatively small the quality of these energies may be large. Nekton feeding was assumed to be proportionately controlled by multiplicative interaction between donor (feed) and receiver (nekton) as suggested by Odum (1972a). Excretion and non-predatory death were approximated by a linear drain (J_{23}), are respiration and predatory death were taken as a function of the nekton stocks to the cubed-power. The basis of this respiration function is the combined effects of density-dependent competition for spatial resources and intra-component predation (fish eating fish) (Odum, 1972a). Respiration is again assumed independent of temperature on the basis of acclimation mechanisms at the organism and community levels (Naylor, 1973; Bullock, 1955). Nekton are assumed to move into the bay populations during the warmer months and out of the bay during the colder months. This migration phenomenon is based primarily on the data of Homer (1976).



$$\dot{F} = k_4 P\cdot F + k_{31} D\cdot F + k_{15} B\cdot F - k_{14} F^3 - k_{23} F + \underbrace{J_{13} - k_{24} F}_{\text{TEMPERATURE - CONTROLLED}}$$

Figure 63. Energy and material input forcing functions for model of estuarine ecosystem shown in Fig. 61: (a) insolation kcal x $10^3/m^2$-day; (b) temperature, °C; (c) turbidity, relative units/m^2-day; (d) nitrogen, g N x $10^{-1}/m^2$-day; (e) seston, g/m^2-day; (f) phytoplankton, g/m^2-day.


(a)
INSOLATION, kcal x 10^{-1}/m^2-day
6
4
2
0
(b)
TEMPERATURE, °C
30
20
10
0
(c)
TURBIDITY, relative units/m^2-day
8
6
4
2
0
DISCHARGE
CONTROL
A M J J A S O N D J F M A M J J A S O N D J F M A
MONTH

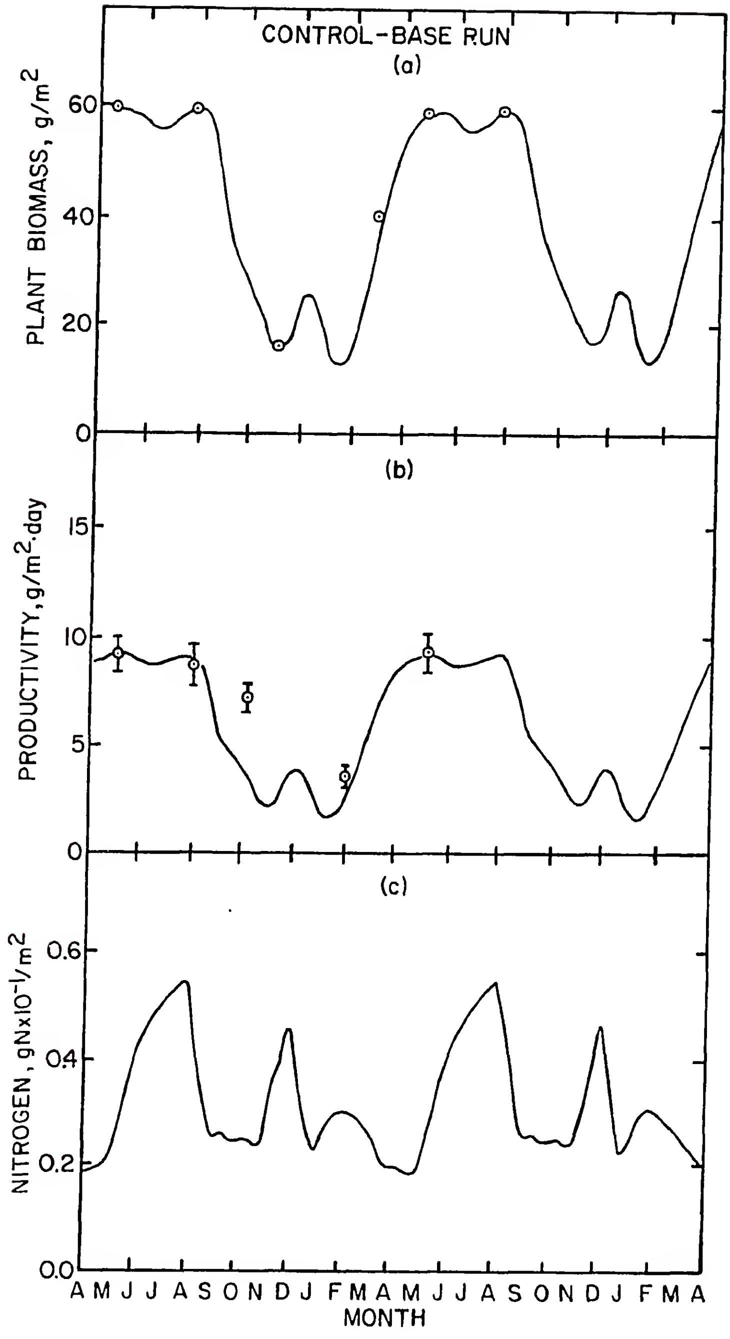

(d)
NITROGEN, gN x 10⁻¹/m²-day
1.0
.8
.6
.4
.2
0
(e)
SESTON, g/m²-day
8
6
4
2
0
(f)
PHYTOPLANKTON, g/m²-day
.5
.4
.3
.2
.1
A M J J A S O N D J F M A M J J A S O N D J F M A
MONTH

most of the data with which this model was developed were collected on a monthly basis, the additional specificity gained by using daily or weekly values for the few parameters where available is unwarranted. Notice that insolation and temperature were about 3 mos (90°) out of phase, with sunlight peaking in May and temperature in August. Turbidity, as indicated from light extinction data, reached a maximum in June for the control system and in July for the discharge. Turbidities were higher in the discharge canal throughout the year; however, this difference was greater during the warm, rainy months (April through October), averaging 37% greater compared to 21% greater during the remainder of the year. Nitrogen, seston and phytoplankton input data all exhibited a tri-modal annual pattern with seston and phytoplankton remarkably synchronous and nitrogen 180° out of phase.

Parameter Optimization and Validation

The model ecosystem's behavior was simulated for both control and discharge conditions and the output of these computer runs is given in Figs. 64 and 65, respectively. The model was simulated for 2-yr periods so that transient behavior at the beginning of the first year could be distinguished from steady-state behavior. The control-condition runs (Fig. 66) were used to optimize the model's pathway coefficients in such a way that model output best corresponded to field data. Seasonal mean values for data were plotted with the model output for comparison, and where available standard-error bars are shown above and below the means. Plant biomass actually intersected the field data points for all four seasons, while model productivity corresponded to the data (within S.E.)

Figure 64. Behavior of estuarine model (Fig. 61) under conditions simulating the control ecosystem, unaffected by power plant discharges. Seasonal mean values of field measurements are plotted with standard error bars (where available) for comparison with model output traces: (a) plant biomass; (b) productivity; (c) nitrogen concentration; (d) benthic biomass; (e) nekton biomass; (f) detritus stocks.


CONTROL-BASE RUN
(a)
PLANT BIOMASS, g/m^2
60
40
20
0
(b)
PRODUCTIVITY, g/m^2·day
15
10
5
0
(c)
NITROGEN, gN×10^{-1}/m^2
0.6
0.4
0.2
0.0
A M J J A S O N D J F M A M J J A S O N D J F M A
MONTH

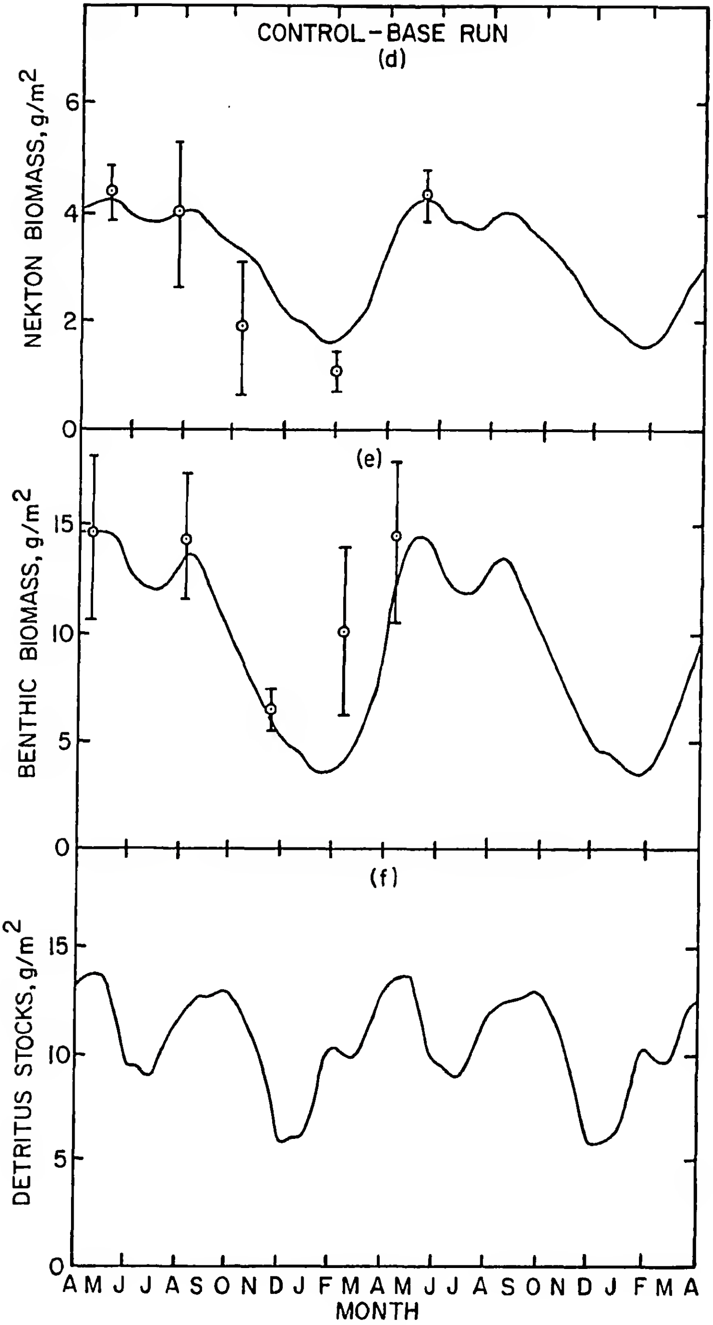
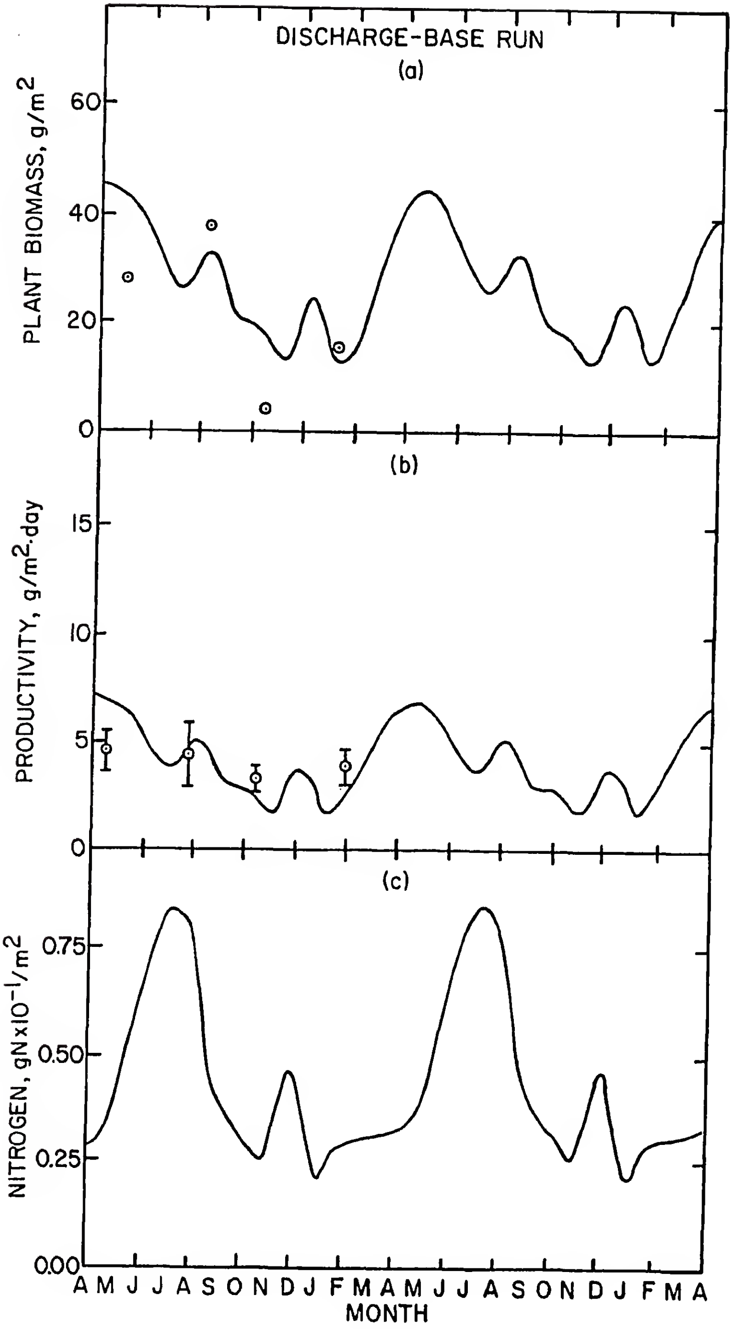
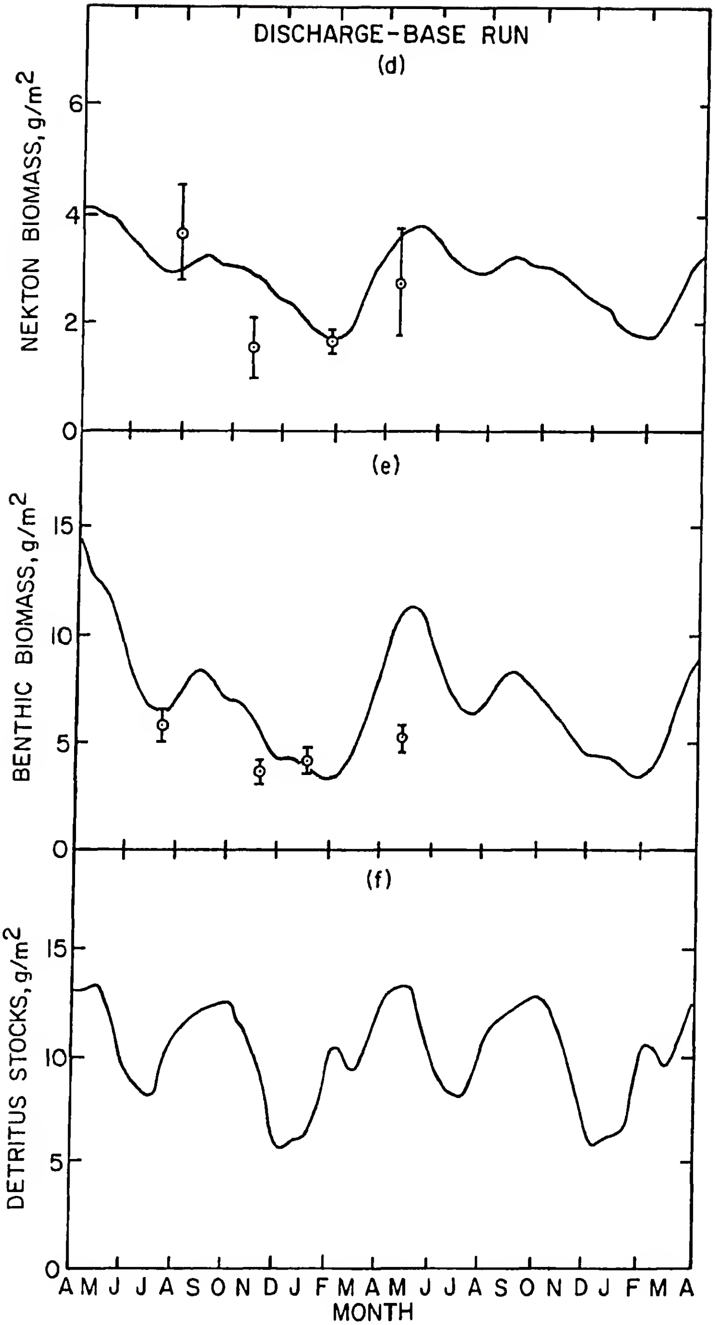

CONTROL-BASE RUN
(d)
NEKTON BIOMASS, g/m^2
0
2
4
6
(e)
BENTHIC BIOMASS, g/m^2
0
5
10
15
(f)
DETRITUS STOCKS, g/m^2
0
5
10
15
A M J J A S O N D J F M A M J J A S O N D J F M A
MONTH

Figure 65. Behavior of estuarine model (Fig. 61) under conditions simulating the ecosystem receiving waste discharges from Crystal River units 1 and 2. Seasonal mean values of field measurements are plotted with standard error bars (where available) for comparison with model output traces: (a) plant biomass; (b) productivity; (c) nitrogen concentration; (d) benthic biomass; (e) nekton biomass; (f) detritus stocks.


DISCHARGE-BASE RUN
(a)
PLANT BIOMASS, g/m^2
0
20
40
60
(b)
PRODUCTIVITY, g/m^2·day
0
5
10
15
(c)
NITROGEN, gN×10^{-1}/m^2
0.00
0.25
0.50
0.75
A M J J A S O N D J F M A M J J A S O N D J F M A
MONTH


DISCHARGE-BASE RUN
(d)
NEKTON BIOMASS, g/m2
0
2
4
6
(e)
BENTHIC BIOMASS, g/m2
0
5
10
15
(f)
DETRITUS STOCKS, g/m2
0
5
10
15
A M J J A S O N D J F M A M J J A S O N D J F M A
MONTH

for all but the autumn conditions where the model output declined more quickly than indicated by the data. The model's benthic invertebrate community trends closely followed the data, except that the data indicated winter populations higher than fall whereas the model did not. Model trends for nekton were the same as the data; however, the data suggested a slightly greater decrease in the winter than shown for the model.

The model equations utilized a total of 23 parameter coefficients which characterize the pathways connecting model variables. Seasonal means of field data for 3 model variables were used to compare with model behavior. Data was used from both control and discharge ecosystems, so that 24 data points (4 seasons x 3 variables x 2 ecosystems) were available. These data were substituted into terms of the model's differential equations to give 24 equations needed to solve 23 parameter values. In reality, all but 6 model coefficients were estimated independently from measurements and estimations of ecosystem stocks and flows. These 6 coefficients were then determined by empirically optimizing behavior of model variables in a trial-and-error process.

The model was "validated" in Fig. 65 under conditions simulating the discharge area. Here, it can be seen that the plant biomass behavior of the model was again reasonably close to the data, except that the data indicated summer standing stocks slightly higher than spring, whereas the model showed just the opposite, and the data indicated an extreme drop in biomass during the fall while the model did not. There was no seasonality in the field data for productivity, whereas the model showed some (though far less than for the control ecosystem). Still, the model output intersected data for all seasons except spring. The data for benthic invertebrates exhibited aseasonal patterns similar to productivity, and the model matched this trend for all but spring conditions in which the model indicated nearly twice the biomass measured in the field. Nekton biomass in the model displayed trends corresponding well to field measurements with the data standard errors intersecting the computer output in all seasons except fall when there was a slight discrepancy.

The relative effects of shading and temperature on primary productivity are shown in Figs. 66 and 67. A 5°C temperature difference between control and discharge ecosystems was tested in Fig. 66, and it can be seen that a 49% decrease in model ecosystem's productivity occurred during the summer months with the increased temperature and turbidity. A 23% reduction of productivity occurred in the discharge system with increased temperature but control levels of turbidity, so that almost half of the depression in productivity resulted from temperature effects alone. Winter productivity was actually higher in the discharge than in the control ecosystem model by as much as 30%. Similarly, plant biomass was diminished in the discharge ecosystem during the warmer months by about 51%, 24% of which is attributable to the elevated temperatures. In Fig. 67 an 8°C temperature difference between control and discharge was investigated, and it was found that the additional 3°C temperature rise (beyond the 2-unit condition with 5°C ΔT) caused an added 19% depression of summertime productivity, bringing the total difference (between control and discharge) to 68%. Here, temperature effects alone accounted for a 46% decrease in productivity, or about two-thirds of the total inhibition. From December through February the productivity in the discharge ecosystem model

Figure 66. Model response to increased temperature and turbidity: (1) control conditions; (2) temperature increased by 5°C; turbidity unchanged; (3) temperature raised 5°C and turbidity increased to discharge levels. Model parameters are (a) productivity and (b) plant biomass.

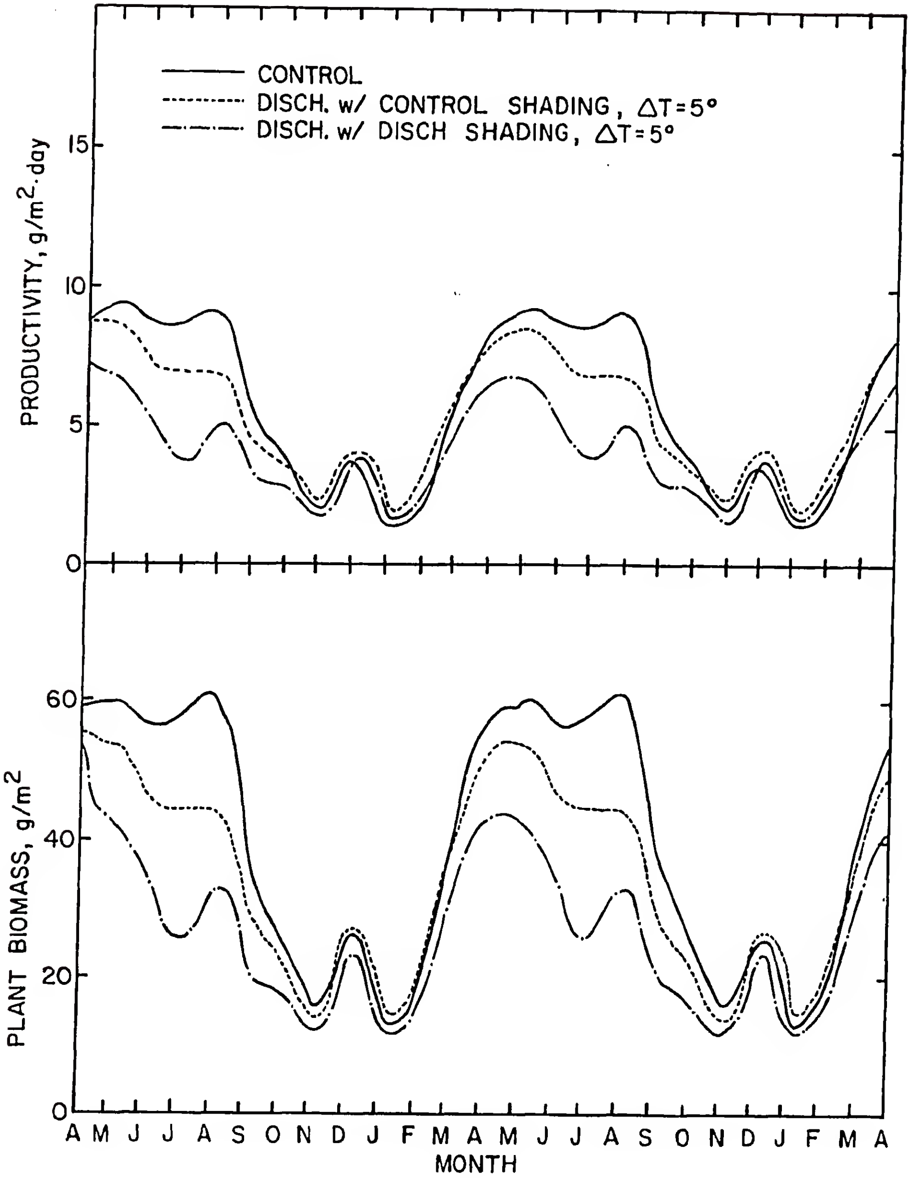
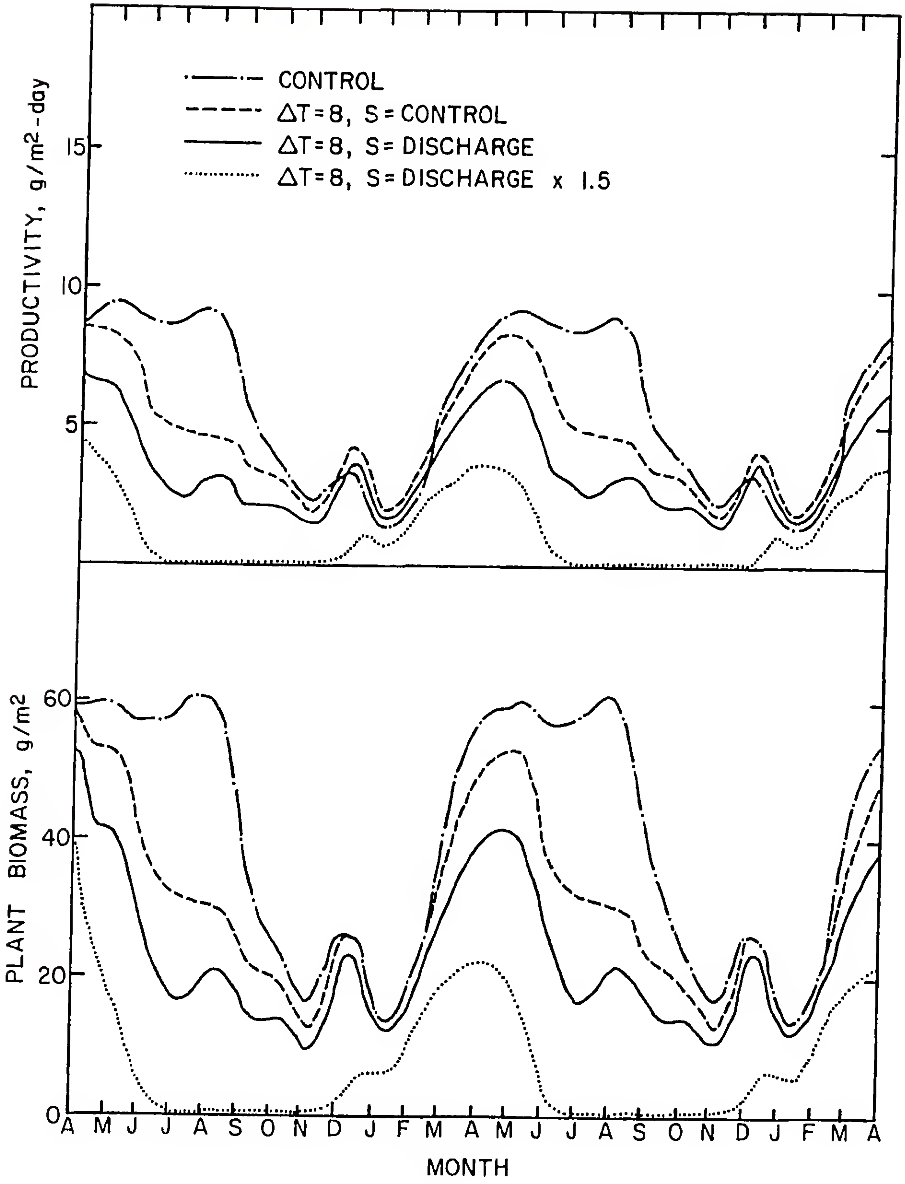

CONTROL
DISCH. w/ CONTROL SHADING, ΔT=5°
DISCH. w/ DISCH SHADING, ΔT=5°
PRODUCTIVITY, g/m2·day
0
5
10
15
PLANT BIOMASS, g/m2
0
20
40
60
A M J J A S O N D J F M A M J J A S O N D J F M A
MONTH

Figure 67. Model response to extreme temperatures and turbidities for conditions simulating Crystal River Units 1-3 operating: (1) control; (2) temperature elevated by 8°C; (3) temperature elevated 8°C, turbidity increased to levels measured in 1974-75 in discharge area; (4) temperature increased 8°C, turbidity increased to 1.5 times the levels in (3). Model parameters examined here are (a) productivity and (b) plant biomass.


CONTROL
ΔT=8, S=CONTROL
ΔT=8, S=DISCHARGE
ΔT=8, S=DISCHARGE x 1.5
PRODUCTIVITY, g/m2-day
15
10
5
PLANT BIOMASS, g/m2
60
40
20
0
A M J J A S O N D J F M A M J J A S O N D J F M A
MONTH

(without turbidity effects) ranged from 25-33% greater than for the control model. As before, plant biomass followed similar trends (Fig. 67).

Sensitivity Analysis

Sensitivity of the model's behavior to the values which were estimated for various pathway coefficients was investigated empirically by consecutive computer runs with different coefficients. The results of these sensitivity tests are given in Figs. 68-74. In the first two figures (68 and 69) the effects of changing productivity coefficients (k_1 and k_p) were investigated. In the Michaelis-Menten or Monod expression for productivity relationships, the two characteristic coefficients, maximum rate (V_m) and half-saturation level (k_s) are directly related to this model's productivity coefficients, k_1 and k_p, respectively. A 25% increase in k_1 resulted in about a 20% increase in productivity, whereas a decrease in k_1 by same percentage yielded a 25-33% decrease in productivity. A 100% increase in k_p gave about a 33% decrease in productivity, while a 50% reduction of k_p resulted in about 25% increased productivity. As indicated by Eppley et al. (1969) the ratio k_1/k_p determines the sensitivity of the model's response to trends in a limiting nutrient. Higher ratios engendered greater sensitivity. Therefore, it can be seen in Figs. 70 and 71 that low values of k_p and high values of k_1 created a model that was hypersensitive to changes in nitrogen. In April as nitrogen concentrations began to build, a sharp pulse in productivity output was observed in the upper curves of both Figs. 68 and 69, and this was followed by a rapid decline and a similar pulse of nitrogen.

The effects of modifying loss rates (respiration, excretion and

Figure 68. Model response to productivity coefficient, k_1: (1) half the normal productivity rate coefficient; (2) normal (control) conditions; (3) 1.5 times normal productivity rate. Model parameters examined here are (a) nitrogen concentration; (b) productivity; (c) plant biomass.

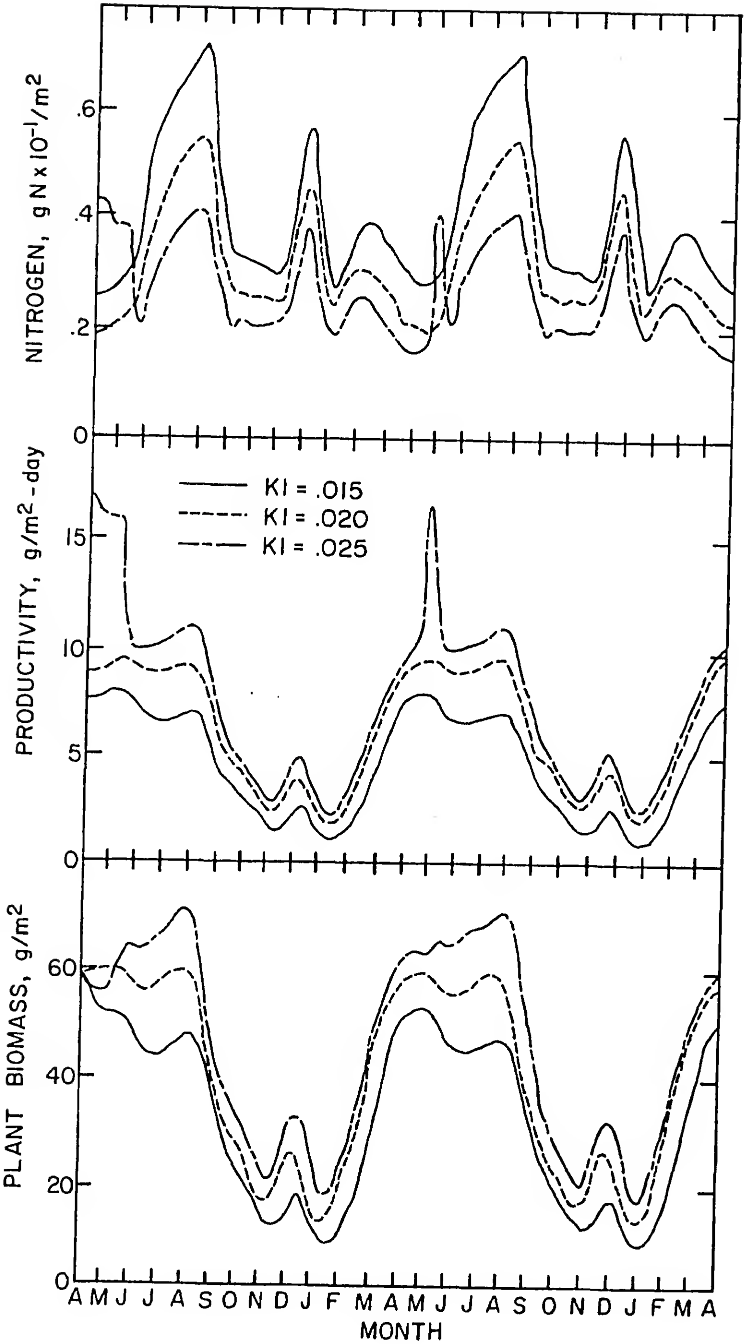

NITROGEN, g N x 10⁻¹/m²
.6
.4
.2
0
PRODUCTIVITY, g/m² - day
KI = .015
KI = .020
KI = .025
15
10
5
0
PLANT BIOMASS, g/m²
60
40
20
0
A M J J A S O N D J F M A M J J A S O N D J F M A
MONTH

Figure 69. Model response to limiting factor "saturation constant," k_p: (1) 2 times normal coefficient; (2) normal (control) conditions; (3) half the normal coefficient. Model parameters examined here are (a) nitrogen concentration; (b) productivity; (c) plant biomass.

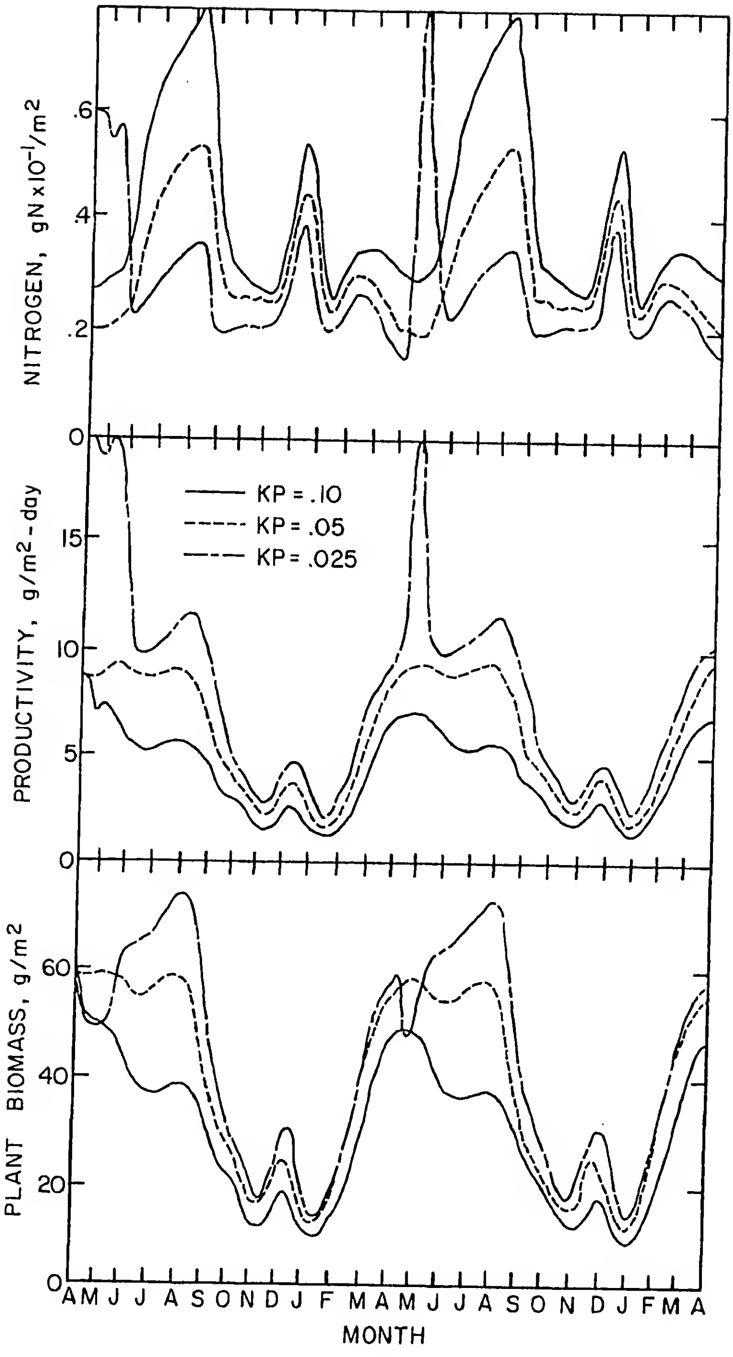

NITROGEN, gN x 10⁻¹/m²
.6
.4
.2
0
PRODUCTIVITY, g/m²-day
15
10
5
0
KP = .10
KP = .05
KP = .025
PLANT BIOMASS, g/m²
60
40
20
0
A M J J A S O N D J F M A M J J A S O N D J F M A
MONTH

Figure 70. Sensitivity of model behavior to plant death rate coefficient, k_6: (1) half the normal death rate; (2) normal (control) conditions; (3) 2 times the normal death rate. Model parameters examined here are (a) plant biomass; (b) benthic biomass; (c) nekton biomass.

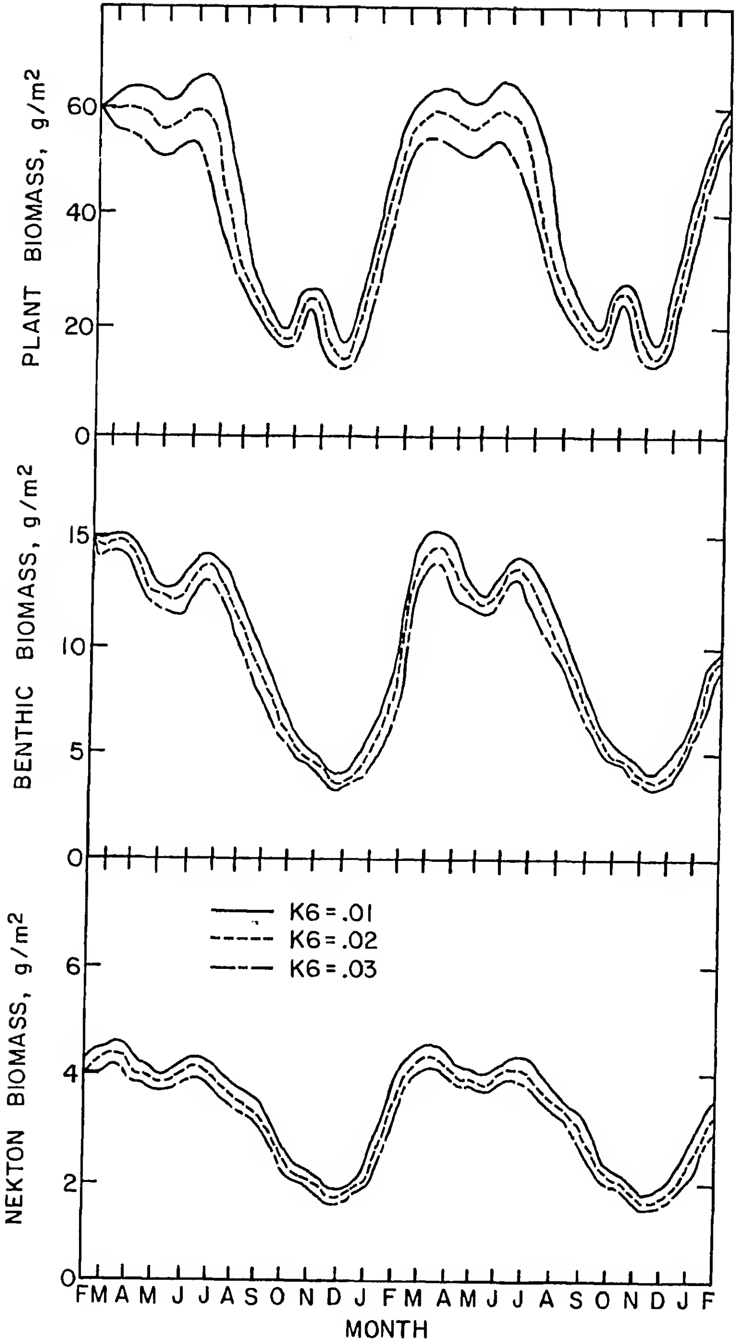

PLANT BIOMASS, g/m2
60
40
20
0
BENTHIC BIOMASS, g/m2
15
10
5
0
NEKTON BIOMASS, g/m2
6
4
2
0
K6 = .01
K6 = .02
K6 = .03
F M A M J J A S O N D J F M A M J J A S O N D J F
MONTH

Figure 71. Sensitivity of model behavior to plant respiration coefficient, k_7: (1) half the normal respiration rate; (2) normal (control) conditions; (3) 1.5 times the normal respiration rate. Model parameters examined here are (a) plant biomass; (b) benthic biomass; (c) nekton biomass.

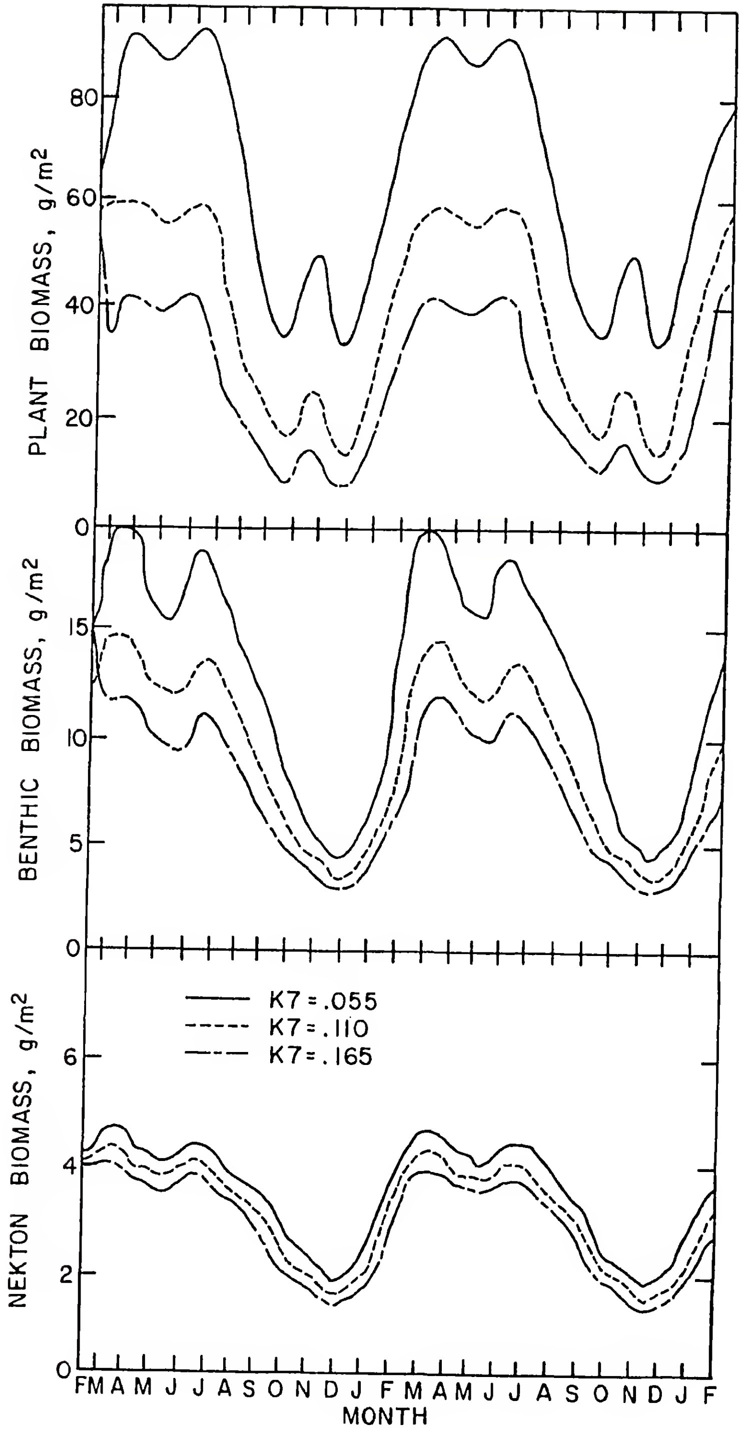

PLANT BIOMASS, g/m2
0
20
40
60
80
BENTHIC BIOMASS, g/m2
0
5
10
15
NEKTON BIOMASS, g/m2
0
2
4
6
K7 = .055
K7 = .110
K7 = .165
F M A M J J A S O N D J F M A M J J A S O N D J F
MONTH

Figure 72. Sensitivity of model behavior to detrital respiration coefficient, k_{19}: (1) twice the normal respiration coefficient; (2) normal (control) conditions; (3) half the normal respiration coefficient. Model parameters examined here are (a) plant biomass; (b) detritus stocks; (c) nekton biomass.

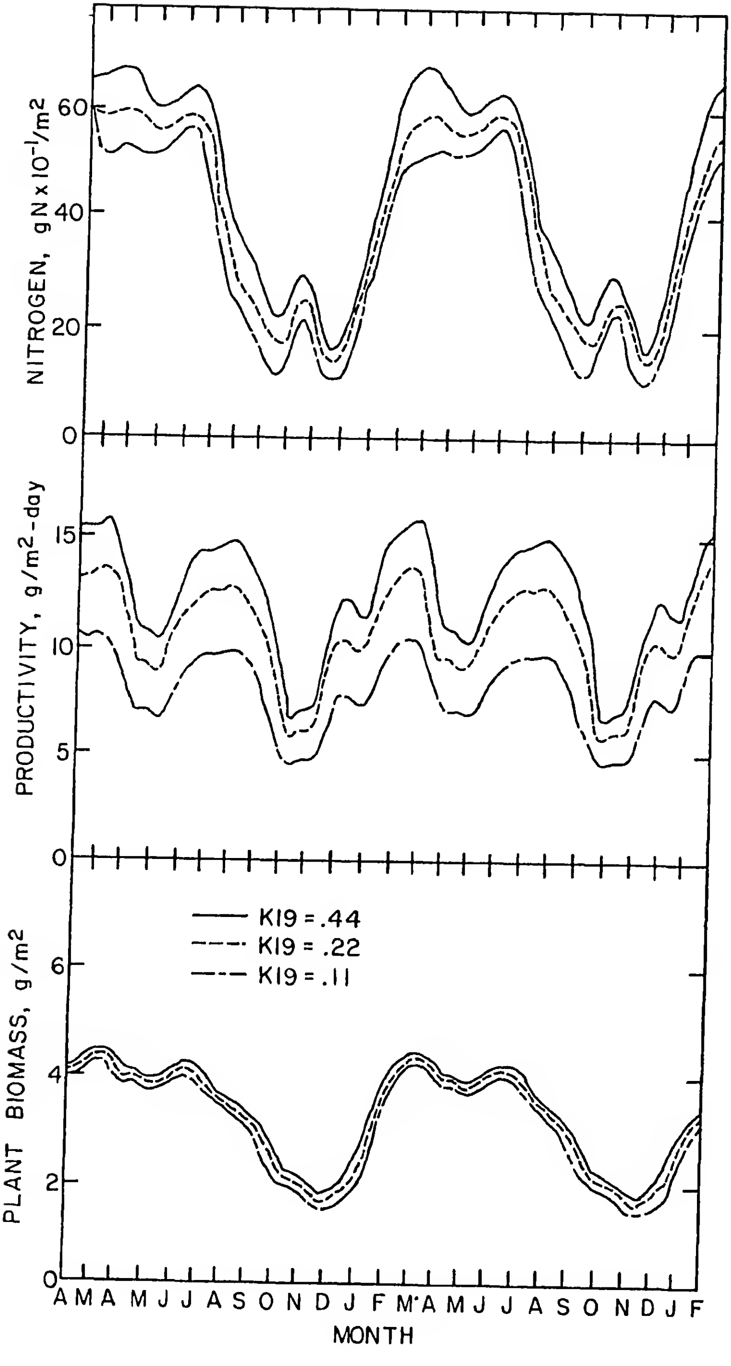

NITROGEN, gN x 10⁻¹/m²
60
40
20
0
PRODUCTIVITY, g/m²-day
15
10
5
0
PLANT BIOMASS, g/m²
6
4
2
0
K19 = .44
K19 = .22
K19 = .11
A M A M J J A S O N D J F M A M J J A S O N D J F
MONTH

Figure 73. Sensitivity of model behavior to nekton respiration coefficient, k_{14}: (1) twice the normal respiration coefficient; (2) normal (control) conditions; (3) half the normal respiration coefficient. Model parameters examined here are (a) plant biomass; (b) benthic biomass; (c) nekton biomass.

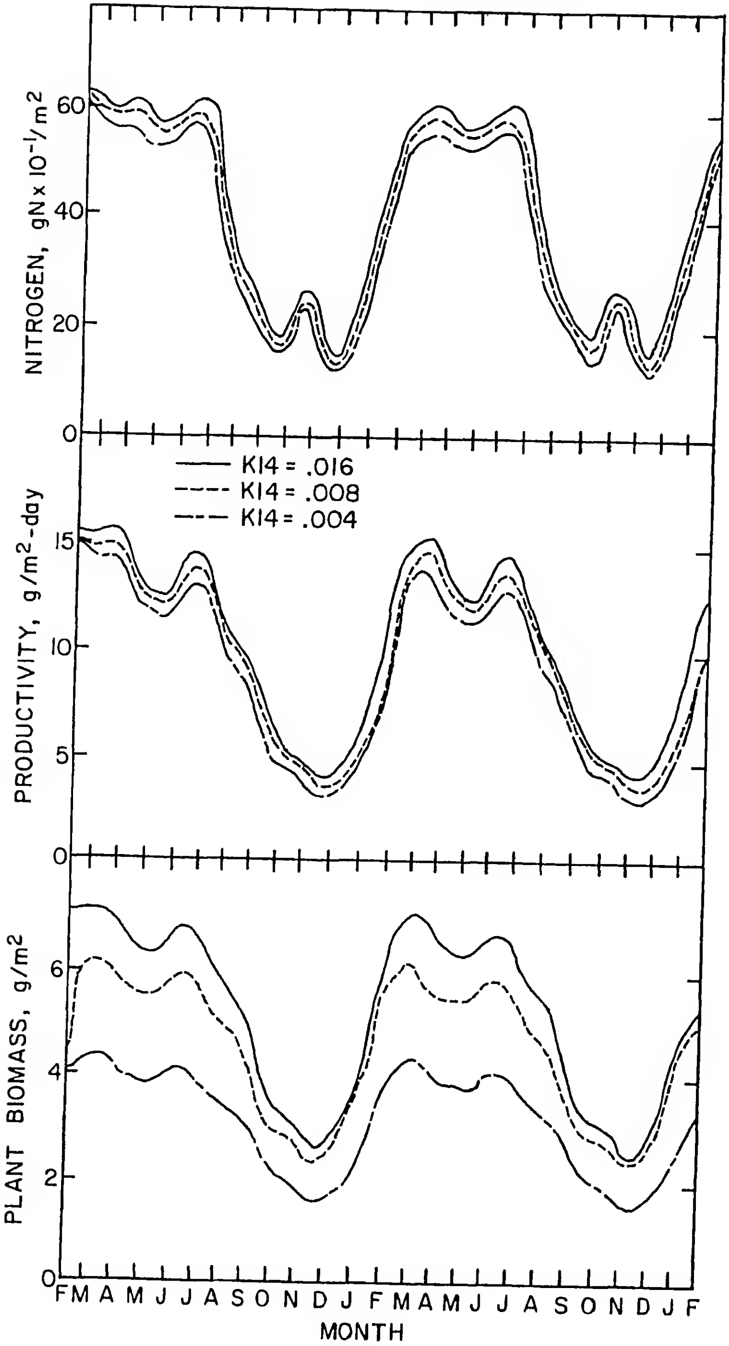
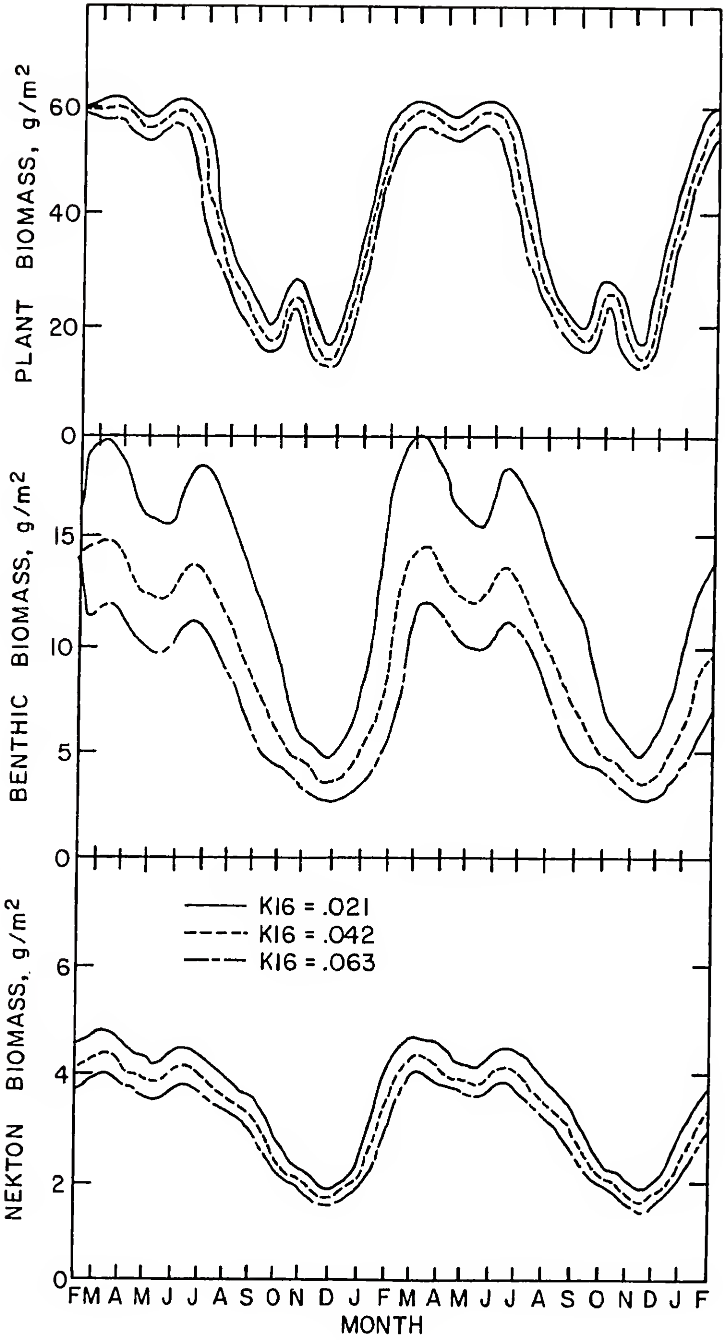

NITROGEN, gN x 10⁻¹/m²
60
40
20
0
K14 = .016
K14 = .008
K14 = .004
PRODUCTIVITY, g/m²-day
15
10
5
0
PLANT BIOMASS, g/m²
6
4
2
0
F M A M J J A S O N D J F M A M J J A S O N D J F
MONTH

Figure 74. Sensitivity of model behavior to benthic respiration coefficient, k_{16}: (1) 1.5 times the normal respiration coefficient; (2) normal (control) conditions; (3) half the normal respiration coefficient. Model parameters examined here are (a) plant biomass; (b) benthic biomass; (c) nekton biomass.


PLANT BIOMASS, g/m²
60
40
20
0
BENTHIC BIOMASS, g/m²
15
10
5
0
NEKTON BIOMASS, g/m²
6
4
2
0
K16 = .021
K16 = .042
K16 = .063
F M A M J J A S O N D J F M A M J J A S O N D J F
MONTH

death) for the major state variables of this model are summarized in Figs. 70-74. A marked difference between a 50% alteration in plant death rate coefficient compared to the same degree of change in plant respiration coefficients was observed. In Fig. 70 it can be seen that these changes in plant death rate coefficient (k_6) led to only about a 12% change in plant biomass, and relatively constant 0.2 and 0.5 g/m^2 modifications for nekton and benthic stocks, respectively. On the other hand, a 50% reduction in plant respiration coefficient (k_7) resulted in about 75% increase in plant standing stocks, a 30% increase in benthics, and 12% rise in nekton biomass (Fig. 71). Inversely, a 50% increase yielded about 33%, 15%, and 10% decreases in plant, benthic and nekton stocks, respectively. In general, the effects of changing respiration coefficients were greatest at the point of the change, diminishing as they cascade down the food chain and feed back to the head of the system. Changing detritus respiration (Fig. 72) by 50% gave about 20% change in detritus stocks, 18% change in plant biomass and a constant 0.2 g/m^2 change in nekton. Modifying nekton respiration rate (Fig. 73) altered its biomass by 18-30%, while benthic and plant stocks changed by some 0.5 and 2 g/m^2, respectively. Finally, when the benthic invertebrates' metabolic rate was altered (Fig. 74) their biomass changed opposite to the rate by 27-33% and the plants and nekton changed by small (< 10%) degrees. The results of these various sensitivity tests are summarized in Table 40.

Model Forecasts

Once some confidence in the model had been gained from the reasonable success in this validation procedure, forecasting simulations were

Table 40. Summary of results from empirical sensitivity analysis of estuarine ecosystem model. Each row represents the percent change in mean annual value for given compartment or flow resulting from given change in parameter coefficient.[a]

Parameter Coefficient	Parameter Description	Percent Change of Parameter	Response of Model Variable (Percent Change)					
			J_1, Productivity	PRD, Plant Biomass	BEN, Benthic Biomass	NEK, Nekton Biomass	DET, Detritus Stocks	NTR, Nitrogen Stocks
k_1	Production Coeff.	-50	-30	-20	--	--	--	+30
		+50	+20	+20	--	--	--	-15
k_p	Limiting Factor	-50	+25	+15	+10	+10	+20	-10
		+100	-35	-20	-30	-30	+5	+35
k_6	Plant Death	-50	+10	+10	+10	+5	0	-10
		+100	-25	-15	+25	+10	+25	+10
k_7	Plant Respiration	-50	+36	+75	+30	+15	+35	-20
		+50	0	-35	-15	-10	-10	+10
k_{19}	Detrital Respiration	-50	+10	-15	-15	+10	+20	-20
		+100	+25	+20	-25	-10	-25	+5
k_{14}	Nekton Respiration	-50	+10	-5	-10	+20	+5	-10
		+100	+25	+10	+35	-25	+20	-15
k_{16}	Benthic Respiration	-50	+25	-5	+30	+15	+10	+5
		+50	+25	+10	-30	0	+10	+10
--	Water Exchange	-25	-15	-10	-10	-5	-10	-15
		-50	-30	-20	-20	-10	-15	-30

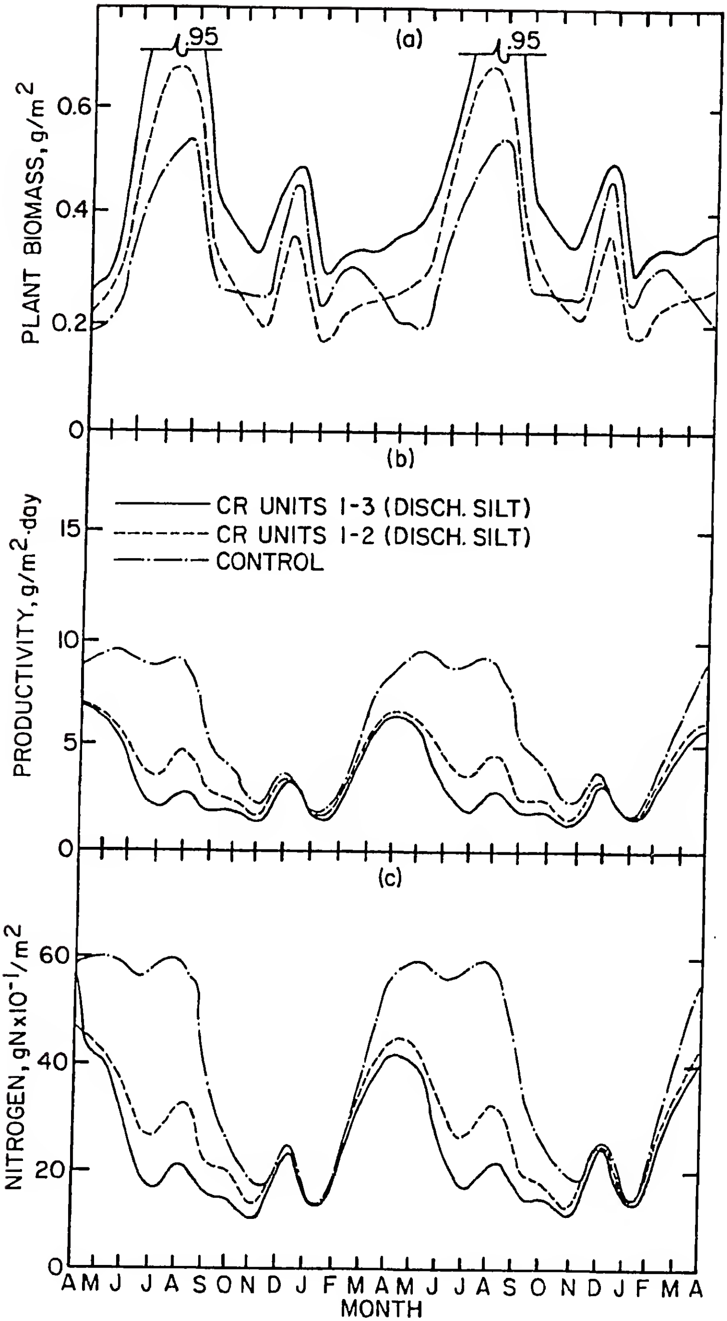
[a] Percent change in model estimated from changes in mean annual values for given vairable. Dashes indicate value not estimated.

undertaken. Results from two forecasting simulations are given in Figs. 75 and 76: (1) Crystal River with units 1, 2 and 3 operating; (2) Crystal River with closed cycle cooling.

The addition of a third generating unit at Crystal River would raise the temperature difference between discharge and control to about 8°C. These conditions were simulated and the results of this experiment are given in Fig. 75. For comparative purposes model behavior for control (3) and present discharge (2) conditions are plotted along with the proposed situation with unit #3 (1). Summer values of productivity and plant biomass (a), which were depressed by about 50% under present conditions in the discharge area, were decreased to only about 33% of the control level. For total annual primary production, an additional 10% reduction (compared to control conditions) was effected by increasing the electric generation rate to 3 units at Crystal River. The effects of power plant operation are greatest between July and October. With reduced productivity nutrient concentrations increase were increased by about 75% beyond control levels. Standing stocks of benthic invertebrates were affected in a manner similar to that for plants, with about 45% reduction in biomass during the warmer months, and about a 5% increase during the winter. The addition of a simulated unit 3 at Crystal River markedly reduced the extent of seasonal dynamics in fish populations, having the added effect of altering fish migration patterns. Only a small impact was observed for the model's detritus variable, ranging from 8-15% reduction in stocks.

A closed-cycle cooling system at Crystal River would eliminate about 90% of the power plant's cooling water flow, which helps to continuously flush the discharge bays with "new" water (Carder et al.,

Figure 75. Model behavior under conditions simulating the shallow bay estuarine ecosystem receiving waste discharges from the Crystal River power plant with 3 units operating: (1) temperature elevation of 8°C with turbidity same as measured in 1974-75 in discharge area; (2) temperature and turbidity as measured in 1974-75 in discharge area; (3) control conditions. Model parameters examined here are (a) nitrogen concentration; (b) productivity; (c) plant biomass; (d) benthic biomass; (e) nekton biomass; (f) detritus stocks.


(a)
.95
.95
PLANT BIOMASS, g/m^2
0.6
0.4
0.2
0
(b)
CR UNITS 1-3 (DISCH. SILT)
CR UNITS 1-2 (DISCH. SILT)
CONTROL
PRODUCTIVITY, g/m^2·day
15
10
5
0
(c)
NITROGEN, gN x 10^{-1}/m^2
60
40
20
0
A M J J A S O N D J F M A M J J A S O N D J F M A
MONTH

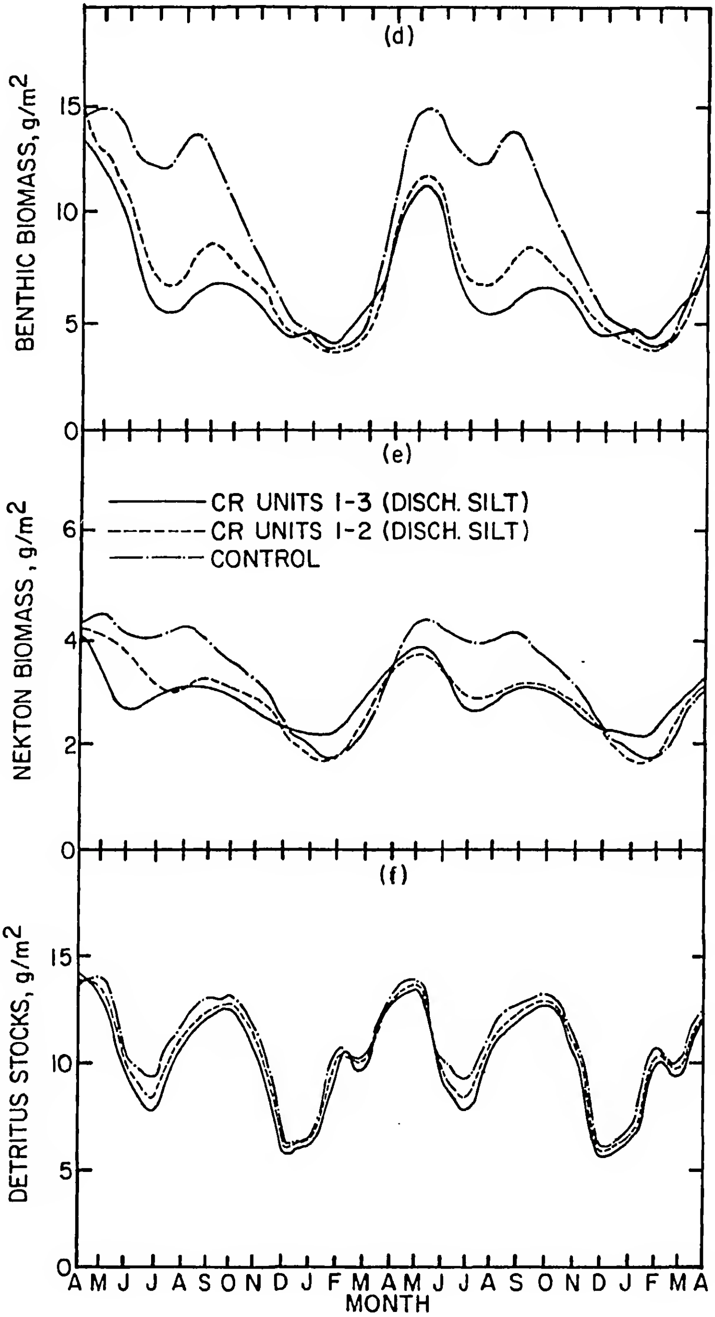
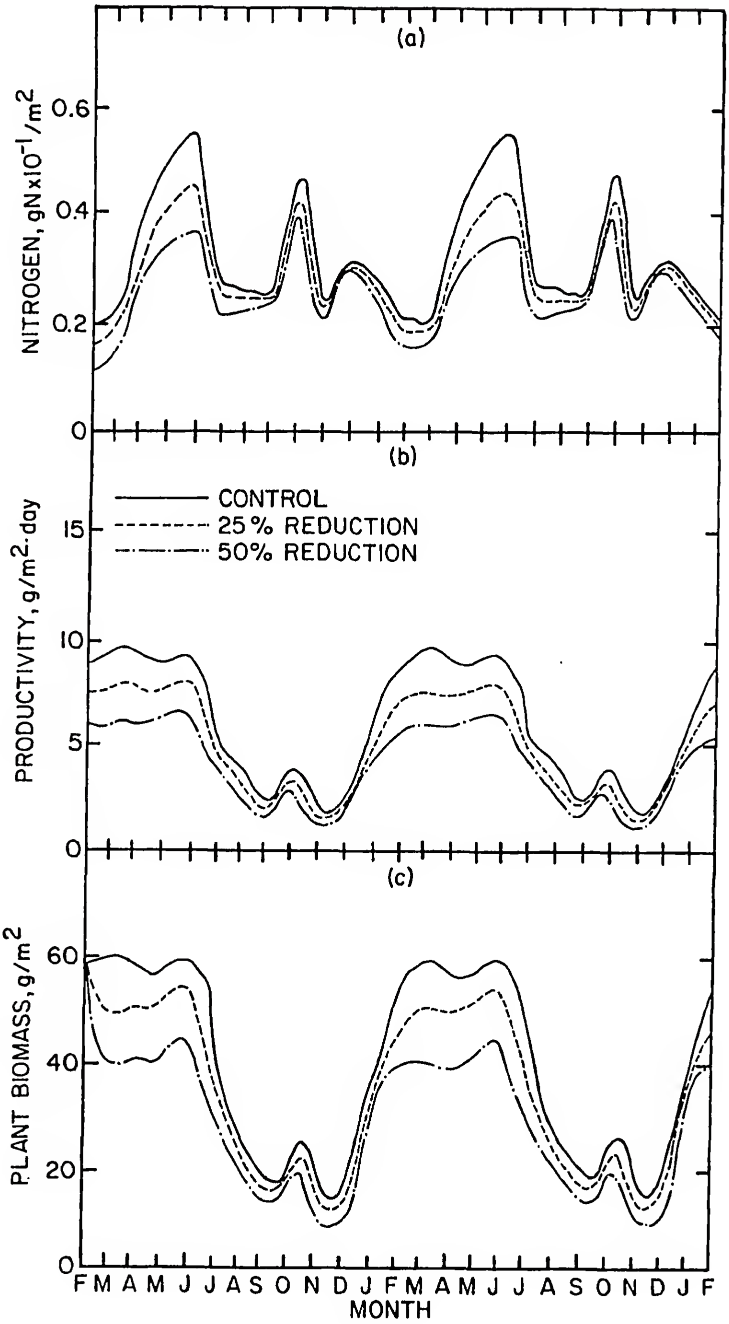
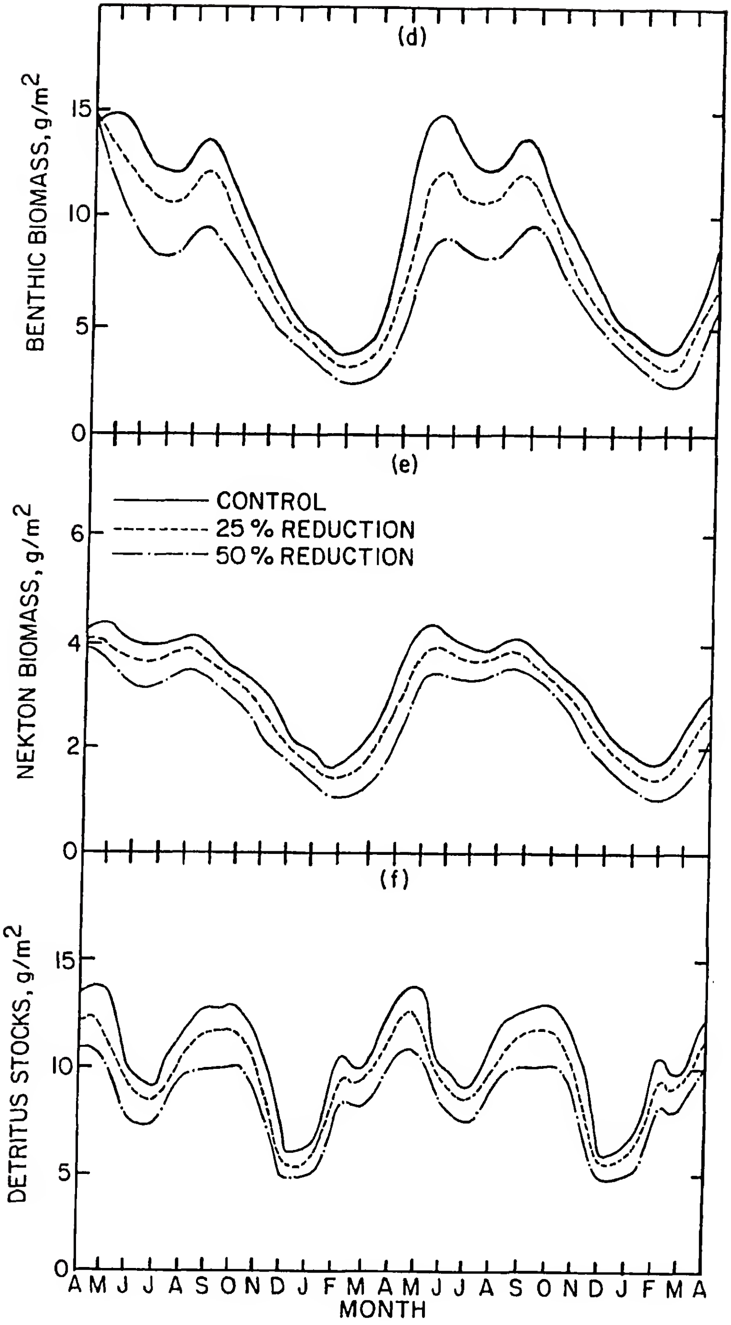

(d)
BENTHIC BIOMASS, g/m^2
15
10
5
0
(e)
CR UNITS 1-3 (DISCH. SILT)
CR UNITS 1-2 (DISCH. SILT)
CONTROL
NEKTON BIOMASS, g/m^2
6
4
2
0
(f)
DETRITUS STOCKS, g/m^2
15
10
5
0
A M J J A S O N D J F M A M J J A S O N D J F M A
MONTH

Figure 76. Model behavior under conditions simulating the shallow bay estuarine ecosystem near the Crystal River power plant, with plant using closed-cycle cooling: (1) control conditions; (2) flushing rate reduced by 25 percent; (3) flushing rate reduced by 50 percent. Model parameters examined here are (a) nitrogen; (b) productivity; (c) plant biomass; (d) benthic biomass; (e) nekton biomass; (f) detritus stocks.


(a)
NITROGEN, gN x 10^{-1}/m^2
0.6
0.4
0.2
0
(b)
CONTROL
25% REDUCTION
50% REDUCTION
PRODUCTIVITY, g/m^2·day
15
10
5
0
(c)
PLANT BIOMASS, g/m^2
60
40
20
0
F M A M J J A S O N D J F M A M J J A S O N D J F
MONTH


(d)
BENTHIC BIOMASS, g/m^2
15
10
5
0
(e)
CONTROL
25 % REDUCTION
50 % REDUCTION
NEKTON BIOMASS, g/m^2
6
4
2
0
(f)
DETRITUS STOCKS, g/m^2
15
10
5
0
A M J J A S O N D J F M A M J J A S O N D J F M A
MONTH

1974). About half of the flushing of the discharge bays was attributable to power plant cooling water flow (Klausewitz, personal comm.). The effect, then, of removing 90% of this flow would probably be to reduce flushing in the bays by 25-50%, depending on the extent to which tidal flushing could compensate for this loss. The results of simulation studies to test the effects of reducing the flushing rate of the bay by 25% and by 50% are given in Fig. 76. In general responses of the model to this perturbation were relatively linear, with reduced imports and exports giving rise to reduced metabolisms and standing stocks. A 25% decrease in flushing resulted in about 15% decline in nitrogen concentration and production, about 10% decrease in plant and benthic animal biomasses, and 6-8% decline in nekton and detritus stocks. By decreasing the flushing rate to 50% of the present level, the effect on model parameters is approximately doubled from the previous case.

DISCUSSION

Cooling Water Canals as Interface Ecosystems

As previously indicated in Table 1, large canal systems have been used at numerous sites to transport water to and from steam electric power plants. The relative importance of these canals as ecosystems is becoming increasingly evident. For example, it has been noted by the AEC (1973a) that the mile-long discharge canal at the Connecticut Yankee Nuclear Plant is "of sufficient size to be considered singularly as a significant aquatic environment." Coutant (1970) has also argued that power plant canals are significant ecosystems, but that they are important not so much in themselves as in their interactions with the natural ecosystems to which they are connected. Hence, Odum et al. (1977) have suggested that these cooling water canal ecosystems be considered as interfaces between power plants and other aquatic ecosystems.

Relationships of Productivity and Respiration

Data provided in this dissertation domenstrate the ability of these interface ecosystems of the power plant canals to adapt to waste discharges and maintain high productivities. Mean annual productivity in the discharge canal at Crystal River was actually slightly higher (1%, not significant) than in the intake canal, whereas gross primary productivity in the shallow inner bays receiving thermal wastes was reduced by about 43% compared to controls (Smith, 1976). Of course, there are substantial morphological differences between the intake and discharge canals, such that the intake canal cannot readily be considered a control for comparison with the discharge. However, only the discharge canal receives power plant wastes, and similarities between the two canal ecosystems may indicate adaptation to these wastes. Seasonal patterns of productivity comparing intake and discharge systems were similar for the canal ecosystems as compared to the shallow bays. Summer production decreased in the thermally affected areas but winter production was stimulated slightly above the unheated systems. This summer-pull, winter-push trend was more pronounced, however, for the bays, and the same pattern has been reported for productivity measurements at numerous other power plant sites (Mihursky, 1971; Flemer, 1974; Morgan and Stoss, 1969; Ford et al., 1975).

Fox and Moyer (1973) measured Carbon-14 plankton productivity at stations along the Crystal River power plant canals. They found that productivity which had been depressed between intake and discharge stations was often fully recovered by the time cooling water had reached the end of the discharge canal. Similarly, the data of Gibson (1975), reported here as Fig. 35, indicated that C-14 productivity was 40-100% higher for sta. 7 at the end of the discharge canal than for sta. 5 at the beginning of the discharge canal, for all seasons except winter. Others (e.g., M.C. Miller et al., 1976) have observed similar trends for discharge canals at other power plants. It might, therefore, be concluded that the discharge canal may effectively function as a buffer to reduce the impact of power plant wastes on the estuarine ecosystems.

Gross productivity for the intake and discharge canal ecosystems was intermediate between the productivities for the bay ecosystems and for the saltmarsh systems. Annual mean productivity (averaged for the two canals was 27% higher than was measured for the outer bays (McKellar, 1975) and 22% higher than that of the inner bays (Smith, 1976) (average for discharge and control), while saltmarsh productivities were about twice as high as canal measurements (Young, 1974b). Plankton productivity contributed a substantial portion of the total community values, averaging 34% of the intake canal and 20% of the discharge canal production, which is intermediate between the planktonic proportions for inner (∿ 15%) and outer (∿ 40%) bays (Smith, 1976; McKellar, 1975). The discharge canal at the Connecticut Yankee plant was also found to be extremely productive, with values for community metabolism typically exceeding measurements in the adjacent riverine/estuarine ecosystem by over 50% (Jacobson, 1976).

Both the intake and discharge canal ecosystems associated with the Crystal River Power Plant were found to be heterotrophic (on an annual mean basis) during this study and in the previous work by Smith et al. (1974). Respiration of the non-plnakton portion of both communities was about 30% greater than was gross benthic community production. Thus, nekton and benthic communities were probably of considerable importance in terms of magnitude of ecosystem metabolic work.

Structure of Animal Communities

In general, the canals were characterized by high concentrations of macroscopic animals relative to the surrounding bay ecosystems. As suggested by Odum and Hoskins (1958) and Nixon et al. (1971), ecosystems such as the power plant canals with swiftly flowing waters may adapt to exploit the subsidy of this kinetic energy. Coutant (1970) has pointed out that this "stream subsidy" coupled with the stress of power plant discharges may lead to shorter food chains (Oksiyuk, 1969) with greater concentrations of animals.

On the basis of annual mean values, the benthic littoral animal community of the discharge canal was less diverse but had similar standing stocks compared to that of the intake canal. Research at other power plants has revealed similar patterns for various kinds of benthic invertebrate communities. Koss et al. (1974) found lower diversity in the discharge canal at the Chesterfield Station on the James River throughout the year, although differences were less pronounced during winter. Kolehmainen et al. (1974) observed identical responses for species diversity of benthic invertebrate communities attached to mangrove roots near a power plant in Puerto Rico, while Jones et al. (1974) reported lower species diversity for benthic animals in the vicinity of a heated water discharge on the Indian River, Delaware during summer only. Logan and Maurer (1975) also found fewer species of benthic invertebrates at discharge canal stations of the same power plant. However, smaller populations encountered in the discharge area overshadowed the reduction in species, so that diversity indices were actually higher for the effluent canal. Young and Frame (1975) also reported lower species diversity, but they found increased numerical abundance of epifaunal organisms attached to artificial substrates in the discharge canal (compared to intake canal) at Oyster Creek power plant, New Jersey.

Massengill (1969) observed 10-40% higher benthic animal biomass in the discharge canal of the Connecticut Yankee Power Plant compared to control stations in the Connecticut River, and Markowski (1960) found higher densities of benthic organisms in the discharge area at a coastal power station in Great Britain. Kolehmainen et al. (1974) also found that their thermally affected stations had slightly greater benthic animal biomass dominated by oysters and barnacles. The epibenthic community in the discharge canal at Chalk Point power plant exhibited greater rates of colonization and growth (as indicated by artificial substrate studies) than for the intake canal ecosystem -- 2.0 compared to 1.1 g ash-free dry matter/m^2-day (Cory and Nauman, 1969; Nauman and Cory, 1969).

Standing stocks of benthic macroinvertebrates were almost identical for the two canals with annual mean biomass for both ecosystems equal to 21.3 g dry organic matter/m^2. These values were 3-6 times higher than standing stocks of benthic animals reported for the bays at Crystal River. This comparison was done by assuming that oyster reefs occupy about 7% of the inner bay area, so that reef biomass estimates of Lehman (1975) were area-weighted with the measurements of Evink and Green (1974) for non-reef communities. Accordingly, it was found that the mean biomass in the discharge and control areas were 5.3 and 12.8 g dry matter/m^2, respectively. Similarly, nekton standing stocks in the canals were more than twice as high (on an annual mean basis) as measured in the bays (3.2 dry/m^2 mean for both canals compared to 1.4 g dry/m^2 for the days (Adams, 1974). Marcy (1971) also found very high standing stocks of fish in the discharge canal at the Connecticut Yankee plant, with an average of 12.2 g dry/m^2 (assuming dry wt/fresh wt = 0.25) being comprised primarily of catfish.

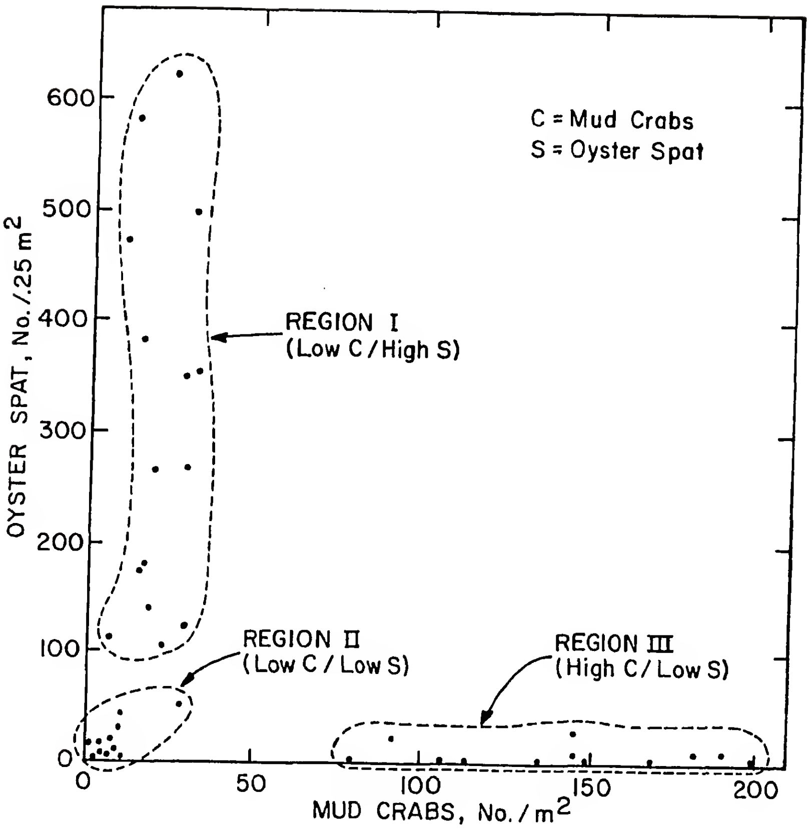
Some Special Adaptations

Ecological communities of the intake canal and discharge canal were exposed to different combinations of environmental conditions. Species composition and other ecological relationships of the benthic communities may reflect adaptations to these different conditions. Standing stocks of benthic animals in both intake and discharge canals were dominated by suspension-feeding organisms (65 and 70%, respectively), where feeding habits were inferred from literature reported for each species (MacGinitie and MacGinitie, 1968; Green, 1968; Newell, 1970). This abundance of suspension-feeders may be an adaptation to the kinetic energy subsidy in the canals. In the intake canal, where rock substrates were less available for attachment (see Fig. A1 of Appendix), biomass of suspension-feeders was dominated largely by the mobile, porcelain crab, Pertrolisthes armatus. Total standing stocks of suspension-feeders were distributed primarily among oysters, barnacles, mussels and serpulid worms, in addition to the porcelain crabs. In the discharge canal, where there is abundant, solid substrate (Fig. B1), total benthic biomass was dominated by two sessile, filter-feeding organisms: balanoid barnacles (40%); and the American oyster, Crassostrea virginica (27%).

The life cycle of oysters in the discharge canal appeared to be somewhat abnormal, with extremely low spat counts (5% of the intake canal) yet relatively high adult standing stocks (2.4 times intake canal stocks). Judging from shell structure and height, the adult population was generally comprised of individuals 3-18 months old (Maurer and Tinsman, 1971; Tinsman and Maurer, 1974). Since the measurements reported in this dissertation covered a 21 month period, it is improbable that this strange disparity between spat and adult populations was attributable only to an unusually low spat set. Xanthid mud crabs, which have been reported as predators on small oysters (Newell, 1970), were the major carnivorous benthic invertebrate in both canals. Three species (*E. depressus*, *E. abbreviatus* and *P. herbsti*) were dominant; however, the larger *P. herbsti* was rarely encountered in the discharge canal, so that the mean size of mud crabs was found to be only one-third as large in the discharge canal. Thus, it may be that these larger crabs were important predators on oyster spat, and in their absence (as was virtually the case in the discharge canal) even the relatively few veliger larvae surviving the stressful passage through the power plant (Kennedy et al., 1974a, 1974b) and setting on the discharge canal substrate, may then experience high survival rates to adulthood.

By this mechanism high standing stock of oysters could, therefore, be maintained with much reduced spat set under the "stressed" conditions of the discharge canal. Pearce (1969) found a similar relationship for benthic communities near the Cape Cod Canal power plant, where elevated temperature resulted in reduced predation by the green crab, *Carcinus maenus*, on the mussel, *Mytilus edulis*. The predator-prey relationship between mud crabs and oysters may be indicated in Fig. 77, where spat density is plotted against crab abundance. An inverse relationship is exhibited with three general regions: (1) low crab abundance with high spat count; (2) low crab abundance with low spat count; and (3) high crab density with low spat count. Region I is comprised exclusively of intake canal data; region III includes only discharge canal data; and region II is mixed with data from both canals.

Figure 77. Oyster spat density versus mud crab abundance in littoral zone of canals at Crystal River power plant for 1973-1975. Region I = high oyster spat density and low mud crab abundance; Region II = low spat density, low crab abundance; Region III = low spat density, high crab abundance.


C = Mud Crabs
S = Oyster Spat
REGION I
(Low C / High S)
REGION II
(Low C / Low S)
REGION III
(High C / Low S)
OYSTER SPAT, No./.25 m2
MUD CRABS, No./m2
0
100
200
300
400
500
600
0
50
100
150
200

Impingement of Nekton

Questions have been raised regarding the extent to which the intake canal may have influenced impingement of nekton. Specifically, did this canal serve more as a funnel, concentrating and channeling fish toward the power plant or as a fertile habitat producing its own fish stocks, part of which were lost to the plant intake screens? It has already been shown that standing stocks of nekton were relatively large compared to surrounding ecosystems, but canal production of these fish populations could not be estimated from the available data. A comparison of standing stock measurements with estimates of migration and impingement rates may, however, shed some light on the relative impact of impingement mortality on the canal populations.

With a mean standing stock of 0.0533 fish/m^2, the intake canal population of polkadot batfish was estimated to be about 24.5 x 10^3 fish in the laterally-confined canal (Table 31). Batfish were impinged at a rate of about 82.8 x 10^3 fish/yr (Snedaker, 1974b), which indicates that drain on the population caused a turnover rate of about 3.3 times/yr. However, immigration of batfish into the canal was estimated to be roughly 63.3 x 10^3 fish/yr, which would turn over the population 2.6 times/yr. Assuming emigration to be negligible, this would indicate that about 20,000 batfish/yr were grown in the canal to be killed on the intake screens. The blue crab population of the intake canal was estimated at about 17.0 x 10^3 crabs, while net immigration was 14.3 x 10^3 crabs/yr, giving a turnover rate of 0.84/yr. Biomass estimates for blue crabs in the canal were about an order-of-magnitude higher than those estimated by Fishler (1965) and Miller et al. (1975) for estuarine ecosystems in N. Carolina and Maryland, respectively. Impingement mortality was about 16.6 x 10^3 crabs/yr for a 0.98/yr turnover rate. Again, this might lead one to believe that a small portion (14%) of the impinged crabs were grown in the canal.

Mean standing stocks of other nekton as measured by gill-netting were about 5.05 g fresh/m^2 in the intake canal. Net immigration was estimated at about 14 g fresh/m^2-yr, replacing the population at a rate of about 2.8 times/yr. Impingement of all organisms except batfish and blue crabs was about 36.6 g fresh/m^2-yr, giving a rapid turnover of 7.2 times/yr. However, 28.8 g fresh/m^2-yr of this impingement was from the Atlantic threadfin pulse. Subtracting this anomalous pulse from the total (under the assumption that it was not from indigenous canal stocks) we find an impingement rate of only 7.8 g fresh/m^2-yr, which is about half of the net immigration rate. This would indicate that, overall, impingement rate was less than immigration rate.

Oesterling (1976) suggested that the intake canal spoil bank was probably impeeding a northward spawning migration of female blue crabs, based on the fact that there was significant difference between catches on the north and south sides of the canal. If this were the case, then it might be expected that, in their efforts to circumvent the spoil bank, a substantial number of crabs may have been funneled into the canal. Once in the canal these crabs would be subjected to potential impingement mortality. Moreover, if the timing of crab migration were adapted to coincide with the spring freshet of the Apalachicola River (Oesterling, personal comm.), a mere delay at Crystal River could result in reduced survival of zoea larvae (Sandoz and Rodger, 1944). Thus, the spoil banks could cause an impact on blue crab populations (or other littoral migrating nekton) for the entire Florida coast.

Entrainment Relationships

In a transect perpendicular to the shore, south of the intake canal, Maturo et al. (1974) found substantial changes in total stocks and species composition from offshore to onshore, with biomass increasing shoreward during winter and spring, and decreasing during summer and fall. Changes were also observed between east and west ends of the intake canal and between intake and discharge canal stations with a general decrease in biomass from the beginning of the intake to the end of the discharge canal (although some groups such as bivalve larvae generally increased along the intake canal). Thus, a considerable percentage (as much as 50%) of the total change in plankton stocks occurring as water flows through the canals, may result from grazing by higher animals in the canal ecosystems, just as grazing also affects populations outside the canals. One might, therefore, compare the system of power plant and canals to a "giant oyster" filtering plankton from the water and excreting detrital matter back to the estuary (Odum, 1974a). Were the estuary limited by metabolic recycling of nutrients, this role of the power plant might serve to stimulate production in the estuary. In fact, during most of the warmer months inorganic-N concentrations were significantly higher in the discharge canal than in the intake (Fig. 43). It appears, however, that at Crystal River other adverse effects of waste discharges may offset any positive recycling effect (see Figs. 27 and 28).

Residence time for cooling water in the discharge canal was about 0.3 days. Coutant (1970) and Pritchard (1971) have emphasized the extent to which time-of-exposure to elevated temperatures in discharge canals can contribute to overall entrainment mortality. Since very little cooling occurs in the discharge canal (Klausewitz, 1973), the residence time in the canal probably increases percent mortality of entrained plankters; however, the magnitude of this effect cannot be ascertained here. One advantage of adding unit 3 will be the fact that residence time will decrease by about 50% and thus percent mortality may also be reduced.

Summary of Benefits and Costs of Canals

In summary, it was found that the construction of cooling water canals has substantially modified the character of estuarine ecosystems near Crystal River. Productivity and other ecological functions of the ecosystems displaced by these canals have been at least partially replaced by the canal ecosystems. Other influences of the canals on the estuary-power plant system which have been discussed in previous paragraphs are less easily quantified. These include the buffering of discharge ecosystems from the stresses of power plant wastes and modifications of entrainment and impingement patterns. The long spoil banks of the intake canal extend well into the Gulf of Mexico and may influence movements of estuarine organisms and of the coastal waters themselves. The effects of intake canal spoil banks on kinetic and turbulent energies have been estimated, but there is presently insufficient information to evaluate the impact on fish and blue crab migrations.

There were also important economic considerations in planning the intake canal. The canal was designed to accommodate fuel oil barges, serving as both channel and port. The next cheapest mode of supplying Crystal River power plant with fuel would have been to transport coal by rail (J.R. Hall, 1975), and therefore the canal resulted in a savings of fuel transport costs. Furthermore, this long intake canal also provided the power plant condensers with offshore water which is as much as 8°C cooler than estuarine water during the hot summer months (McKellar, 1975). This cooler water permitted higher carnot efficiencies which in turn yielded more effective conversion of fuel into electricity.

Some of the important energy costs of the Crystal River power plant canals which have been estimated are summarized in Table 41. The effects on estuarine productivity and hydrodynamics indicate about 42% decrease in the estuary's energy value. However, it appears that economic factors far overshadow this ecological impact (by almost 3 orders-of-magnitude). The differential cost between barge and rail transport of fuel amounts to some 370 x 10^9 kcal CE/yr (\$18 x 10^6). The energy benefit of cooler, offshore water was estimated to be about one-third of this (130 x 10^9 kcal CE/yr), which is still more than 100 times greater than the total canal productivity. It is thus seen that the canals were economically important design features for the Crystal River power plant. The canals, themselves, were highly productive estuarine ecosystems, and the main ecological cost of the canals was associated with relatively low productivities of the sparse ecosystems on their spoil banks.

Energy Quality Relationships

Calculations provided in this dissertation and elsewhere and summarized in Table 5, seem to indicate that energy quality ratios of

Table 41. Summary of energy costs involved in construction and operation of cooling water canals at Crystal River.

Energy Costs x 10^9 kcal CE/yr	Design Alternatives: With canals	Design Alternatives: Without canals
Economic Effects[a]		
Cost of Canals[b]	-3.40	0
Increased conversion effic. with cooler water[c]	0	-128.22
Fuel transport cost[d] differential	-326.97	-695.52
Subtotal	-330.37	-823.74
Environmental Effects		
Coastal hydrodynamics[e]	-0.16	0
Displacement & replacement of ecosystems[f]		
Bays	-0.96	0
Marshes	-0.82	0
Canals	0	-1.02
Subtotal	1.94	1.02
Totals	332.31	824.76

Table 41. (Continued)

[a] Monetary costs are converted to energy costs using 20,000 kcal/$ (Kylstra and Han, 1975).

[b] Capital cost of dredging intake canal was 2.966 x 10^6 dollars, while discharge canal construction cost 0.596 x 10^6 dollars. Assuming a 30 yr design life and converting to 1973 equivalent dollars, this amounts to about 0.17 x 10^6 dollars/yr, which is about 3.40 x 10^9 kcal CE/yr. Data is from J.R. Hall (1975).

[c] Assumes about 0.8% turbine backpressure penalty (Gilbert Associates, 1974). In coal equivalent energy terms this cost is,

$$6754 \text{ KW } (8760 \text{ hr/yr})(.70 \text{ load})(3096 \text{ kcal CE/KWH})$$
$$= 128.22 \times 10^9 \text{ kcal CE/yr.}$$

[d] Assume: power plant burning coal; coal would necessarily be transported by railroad without canals; coal source is 1000 miles from power plant site; costs of handling are same for either mode. Costs are 1840 BTU/ton-mile by rail and 865 BTU/ton-mile by barge (Bayley et al., 1976c).
Assume about 1.5 x 10^6 tons/yr would be needed (Shrode et al., 1975) at Crystal River. Thus,

$$\text{By Rail} = (1840 \text{ BTU/ton-mi})(1.5 \times 10^6 \text{ ton})(1000 \text{ mile})(.252 \text{ kcal/BTU})$$
$$= 695.52 \times 10^9 \text{ kcal CE/yr}$$

$$\text{By Barge} = (865 \text{ BTU/ton-mi})(1.5 \times 10^6 \text{ ton})(1000 \text{ mile})(.252)$$
$$= 326.97 \times 10^9 \text{ kcal CE/yr.}$$

[e] Estimated reduction in transport energies. See Table 42.

[f] Productivities of estuarine ecosystem replaced by canals and for canals themselves. See Table 23.

various natural energy inputs to this study region are generally similar, ranging from 0.1 CE (wind) to 3.1 CE (chemical potential of fresh water). Each of these energies (except tides) is generated in some way from solar radiation, and they represent an upgrade in quality from that of sunlight by a substantial factor (200-6000). The relatively high quality of fresh-water helps to explain why water is valued so highly, particularly in dry climates and densely developed areas (H.T. Odum, 1970).

An interesting pattern was demonstrated in the energy computations for waves, where the quality of wave energy was found to increase logarithmically with increasing concentration of waves (i.e., larger, more energetic waves in a given locale). This trend was further indicated for the two situations in which tidal energy was investigated. Tides at the Bay of Fundy (9.9 meter amplitude) generate more energy than the 7.4 meter tides of La Rance, and it was calculated that the former in-turn may be able to generate more electric power per unit tidal energy than the latter. Similarly, it was shown that the detritus branch of an estuarine food web was able to generate much higher quality organisms than did the grazing branch. This may be a function of the fact that in this ecosystem about ten times more energy was channeled into the detritus branch, so that greater concentrations of energy were able to develop higher quality units. It may be that such a relationship exists for the chemical potential of fresh water (e.g., the free energy of distilled water may be higher quality than the free energy of tap water), but if so it was not accessible from the data presented in this study.

Another relationship may have been operant in the desalination data assembled herein. This concept is related to the "limiting factor" principle of ecology (H.T. Odum, 1971; E.P. Odum, 1971), where the value of a given resource in a given ecosystem is a function of the extent to which that resource is limited in the particular system. Thus, a liter of fresh water is more valuable in a desert region than in a rainforest (H.T. Odum, 1970, 1971). The desalination data used here to calculate energy quality of fresh water was taken entirely from situations for insular or arid regions where water is scarce. Therefore, the quality of fresh water's chemical potential as calculated from this data, may be somewhat higher than the quality which is relevant to a relatively wet climate such as Florida (receiving some 130 cm of rain per year).

The energy qualities of some estuarine animals were found to be considerably higher than that of coal. Qualities estimated for organisms considered in this study ranged from about 1.2 CE for striped mullet to 14.9 for Crevalle jack. The blacktip shark, whose diet at Crystal River is described in Appendix Table C5, was estimated to have a quality of about 31.0 times greater than coal. Thus, it is seen that the information content of these upper trophic level organisms with complex behavioral programming may engender them with high quality energetic characteristics. Certain organisms of lower trophic levels, such as the striped mullet, also contribute substantial energy value to the ecosystem because (even at lower quality) their total energy flow is so vast.

Energy Effectiveness of Environmental Technology

In previous sections of this dissertation, detailed analyses were provided to estimate effects of the Crystal River power plant on estuarine ecosystems with which it interacts. Environmental effects of the power plant were documented for present conditions and computer simulations of an ecological model were used to estimate effects of proposed alternative operating conditions (namely: addition of unit #3; and closed-cycle cooling). When converted to energy units of equivalent quality, the various environmental effects considered in this study can be compared to one another. Moreover, these effects can also be contrasted to the energy costs associated with economic investment for tehcnological facilities which may reduce these direct ecological effects (e.g., cooling towers). By comparing the costs of ecological damage from power plant operation with the costs of economic investment to mitigate this effect, we may add some insight to the more general question as to the energy effectiveness of environmental technology.

The ecological effects of power plant construction and operation under present conditions and with addition of unit #3 are summarized in energetic terms as Table 42. This composite of Tables 13-26 indicates that the present total, direct, ecological damage from cooling water circulation amounts to some 5.3×10^9 kcal CE/yr, while the addition of unit #3 brings this total to 10.9×10^9 kcal CE/yr. It can be seen that entrainment of meroplankton is by far the greatest cost, with entrainment of juvenile fish and inhibition of estuarine primary production contributing substantially to the overall loss. Even before the power plant began operation, construction at Crystal River resulted in an ecological impact of 2.4×10^9 kcal CE/yr with 2 generating

Table 42. Summary of ecological and energetic costs to the Crystal River estuarine and regional systems resulting from power plant operation.

Category of Ecological Effect[a]	Energy Costs, kcal CE x 10^6	
	2 Units Operating	3 Units[b] Operating
Effects of Cooling Water Systems		
1) Entrainment of Zooplankton:		
- Ecological Work of Plankton	141	292
- Ecological Work of Surviving Adult Organisms	2544	5266
- Economic Value to Region	1010	2091
2) Juvenile Fish Entrainment:		
- Ecological Work of Juveniles	652	1350
- Ecological Work of Surviving Adult Organisms	19	39
3) Nekton Impingement:		
- Ecological Work	152	315
- Economic Value to Region	17	35
4) Reduced Ecological Metabolism:		
- Bays	327	648
- Marsh	476	839
Subtotal	5338	10,875
Effects of Power Plant Structures:		
1) Displaced Ecosystems:		
- By Canals	-1781	-1781
- By Power Plant	-1488	-1980
2) Replacement by Canal		
- Ecosystems	+1024	+1024

Table 42. (Continued)

Category of Ecological Effect[a]	Energy Costs, kcal CE x 10^6	
	2 Units Operating	3 Units[b] Operating
3) Effects on Coastal Hydrography:		
- Spoil Banks Effects		
Kinetic Energy	-59	-59
Turbulent Energies	-100	-100
- Power Plant Plume	+12	+98
Subtotal	2392	2798
Total Power Plant Effects	7738	13,673

[a] Refer to Tables 13-22, and Figs. 20-29 for calculation of energy effects for each of these categories.

[b] Entrainment and entrapment were estimated for three-unit power plant operation by assuming a linear relationship between cooling water flow and animal mortality.

units and an estimated 2.8 x 10^9 kcal CE/yr with unit 3 added.

In Table 43 the environmental effects under 3 alternative cooling water systems are given in both energy and economic terms and are compared to the economic investment involved in each management system. In economic equivalents the annual environmental impacts of power plant construction and operation were about $140,000 and $550,000, respectively ($690,000/yr total). These environmental losses represent over 4% (.69/16.22, Table 42) of the cost of closed-cycle cooling. Cooling technologies, themselves, result in direct environmental impacts: (1) causing additional displacement of natural ecosystems; (2) requiring 10% make-up water; and (3) causing stress on surrounding terrestrial ecosystems from salt-spray deposition. Therefore, overall environmental impact would be reduced by only 62% (1 - (.26/.69), Table 43) using modular spray systems and 42% (1 - (.40/.69), Table 43) for mechanical draft cooling towers. The net reduction of ecological costs using closed-cycle cooling would be only 2.7% (.69 - .26)/16.22) and 1.6% (.60 - .40/18.02) of the economic investment for modular spray and mechanical draft tower systems, respectively.

A secondary effect of the ecological costs of present power plant operation is included in Table 43. This effect is the reduced ability to attract capital (fossil fuel) investments from outside the region. The significance of this effect is based on the assumption that investment of fossil fuel-based capital is attracted ultimately by availability of free energies from nature. These natural energies would enhance the ability to profit from such investment, since a lower percentage of the total energy involved in the output products of the investment would be derived from expensive fossil fuels. In the U.S.

Table 43. Comparison of energetic and economic costs of the Crystal River power plant region for three alternative cooling water management schemes for 3 power plant units operating.

Category of Energetic or Economic Cost	Open-Cycle System Once through Cooling		Closed-Cycle Cooling Systems[a]			
			Modular Spray System		Multi-Cell Mech. Draft	
	Energy Cost, kcal CE x 10^9/yr	Economic Cost, \$ x 10^6/yr	Energy Cost kcal CE x 10^9/yr	Economic Cost, \$ x 10^6/yr	Energy Cost kcal CE x 10^9/yr	Economic Cost, \$ x 10^6/yr
Direct Impact on Environment:						
- Effects of Cooling Water[b]	10.9	0.55	1.3	0.07	1.3	0.07
- Effects of Cooling Structures[b,c]	2.8	0.14	3.7	0.19	6.5	0.33
Loss of Investment Attraction[d] Potential to Environment	37.0	1.85	13.5	0.68	21.1	1.06
Cost of Environmental[e] Protection	2.9	0.12	324.9	16.22	360.9	18.02
Total Cost	53.9	2.65	343.4	17.16	389.8	19.48

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[a] Data used from Gilbert Associates (1974). See Table 24. Economic and energetic values are interconverted assuming 20,000 kcal/\$ (Kylstra and Han, 1975).

[b] Refer to Table 41. Entrainment and entrapment effects estimated by assuming 10% make-up water and linear relationship of water flow and mortality. Metabolism effects estimated from behavior of simulation model with reduced flushing, Fig. .

Table 43. (Continued)

[c] Includes net displacement effect of canals and other cooling systems plus salt spray effects. Table .

[d] Based on the assumption that investment of fossil fuel energies is attracted by the availabilty of free energies provided by nature which enhance the ability to profit from such investment. The adaptive match of fossil fuels to natural energies is that of U.S. economy (2.7).

[e] Includes cost of canal construction and maintenance, assuming 30 year design life (Hall, personal comm.).

and other nations there may be an inherent adaptive tendency to match the natural energies in a given region with fossil fuel-based energies at a ratio equivalent to the investment ratio for the entire national economy. This ratio was 2.7 in the U.S. for 1973 (Kylstra and Han, 1975). Therefore, in Table 43 we see that the total loss from the Crystal River region (including this loss of investment potential) could be as high as 37.0×10^9 kcal CE/yr, which is 11.3% of the cost of the cheapest cooling technology. It may be, however, that these secondary effects are not comparable to the direct costs of cooling towers, since no secondary factors were included in the latter.

The money which would be invested in cooling tower construction, operation and maintenance represents a diversion of fossil fuel energy from other possible investments into the economy of man and nature which could return a greater income to the system. By way of perspective, the cost of cooling towers for the Crystal River (3-unit) power plant is about equivalent (in terms of work value) to complete inhibition of primary productivity in an estuarine region equivalent to about 0.1×10^9 m^2 or 40 mi^2 (considering also the loss of investment potential). The energy flowing through the U.S. national economy to supply 16.2 million dollars worth of goods and services to build and maintain a cooling tower is estimated to be 73% from purchased fossil fuels and 27% from the free services to the economy from work of the environment such as absorbing and recycling wastes (according to the 2.7 ratio given in previous paragraphs). In other words, 27% of the energy cost of the cooling towers represents environmental interactions elsewhere. This effect amounts to about 87.7×10^9 kcal of coal work equivalents per year which is about 7 times greater than the 13.7×10^9 kcal CE per year projected as the impact on the estuary of the Crystal River power plant.

The energy analyses done in this report represent very conservative set of assumptions, that is, calculations were done for the "worst" conditions which were reasonably conceivable. Tabulations of energy and economic equivalents for ecological effects of power plant operation indicate that the total impact of the plant on the estuary may be substantial. However, compared to the total energy budget of the plant this is very small (< 0.1%), and compared to the cost of cooling towers this ecological impact is only 4 percent. It is therefore concluded that economic and energetic investment in cooling towers to help relieve ecological effects of the power plant at Crystal River would be unwise. Such an investment would be a non-competitive use of limited energy reserves.

Odum and Kylstra (1976) discussed the relative merits of environmental technologies in general. They concoluded that most technological waste treatment systems are fossil-fuel-intensive, amking inadequate use of natural energies to contribute to the treatment process. Furthermore, they suggest that interface ecosystems be "cultivated" for use in place of environmental technologies. The ratio of fossil fuels to natural energies involved in these treatment processes was used as an index of the relative intensity of applying fossil fuels. Comparing this ratio for technological treatment of sewage wastes in the U.S. with the ratio of fossil fuels to natural energies supporting the national economy, indicated that sewage treatment technology require what may be excessive fossil-fuel-based investments. On the other hand, Mitsch (1975) found that this ratio for non-technological tertiary treatment systems using cypress wetlands as interface ecosystems was nearly the same as the overall ratio for the U.S. economy. It is difficult at this point to extrapolate to a generalization about power plants and environmental technologies. However, a similar energy benefit-cost analysis as given in this dissertation was done for another power plant at Anclote Key, Florida (Kemp, 1976) and likewise indicated cooling towers as a poor energetic investment.

Energy Signature of Crystal River Estuary

In a comprehensive literature review Odum et al. (1973) developed a detailed scheme in which the coastal ecosystems of the United States were categorized on the basis of energy influences. They argued that the general ecological character of estuaries is directly dependent on the energy forcing functions (such as waves, tides, runoff, and industrial wastes) input to these systems. They recognized that biological details of such ecosystems may vary according to geographic and probablistic factors, with replacement and "parallelism" (Thorson, 1966) determining the exact species composition of available niches. However, adequate evidence is provided to indicate that the structure and function of coastal ecosystems arises largely from their associated energy regime.

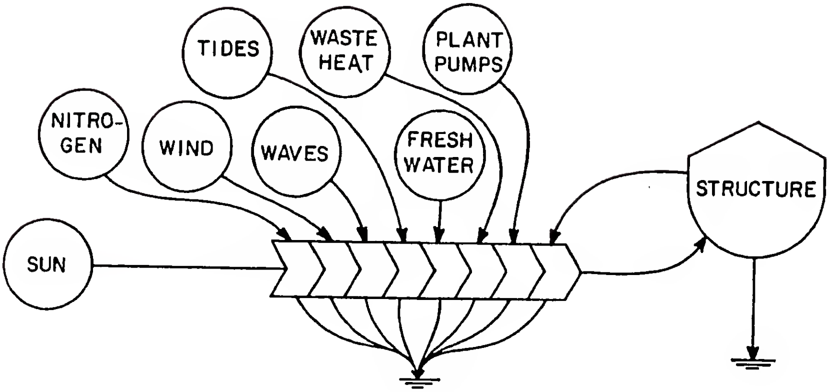
While Odum et al. (1974b) clearly established this principle of energetic-ecological causality, their criteria for ecosystem categorization were only partially quantitative. In a recent, unpublished report investigating interactions between dredging operations and the coastal ecosystems of Florida, Odum and Bayley (1976) established more precise definitions. They have described the energies which influence these estuarine ecosystems as the ecosystem's "energy signature." The theory of energy signatures was described in Odum et al. (1977), where comparison of energy flows in units of the same quality indicates their relative importance in generating work and control functions in the system. Energy signatures were shown to correspond to the biotope concept whereby the character of ecosystems could be predicted from knowledge of environmental factors.

An energy signature for the estuarine ecosystem adjacent to the power plant at Crystal River is calculated and provided in Fig. 78. In general there is great need to develop workable, gestalten descriptions of the energetic character of various ecosystems interacting with power plants. If a relationship could be developed between energy signature and extent of ecological effects, such information might be integrated into a power plant siting code. While such an effort is beyond the scope of this study, the energy signature provided herein may serve as a first step toward this end.

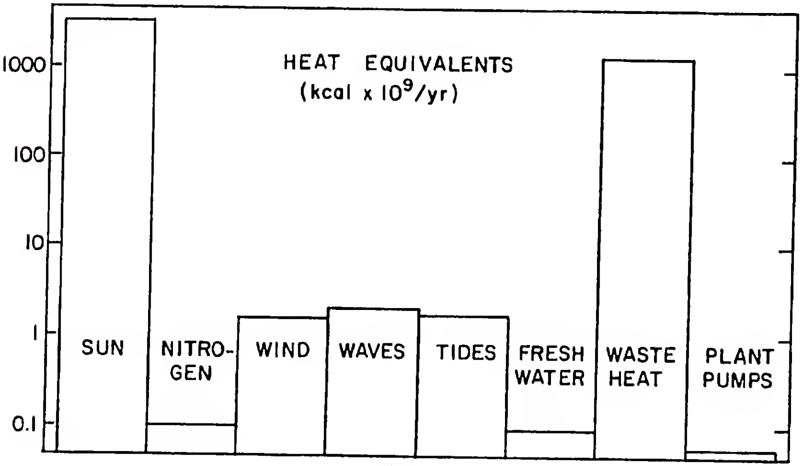
External energies flow into the Crystal River area and interact in a number of work processes to build system structure such as tiers of biological standing stocks (trophic levels). Other non-living organization is developed from these energies in such physical forms as sand bars and marsh creeks, spectra of water turbulence and density gradients. A summary diagram of the many kinds of energy is illustrated in Fig. 78a.

The energy signature for Crystal River is given in Figs. 78b and c. Calculations are made for the estuary including both inner and outer bay areas receiving the power plant discharge. This area is arbitrarily defined as a square, 1.5 km on each side enclosing the inner and outer

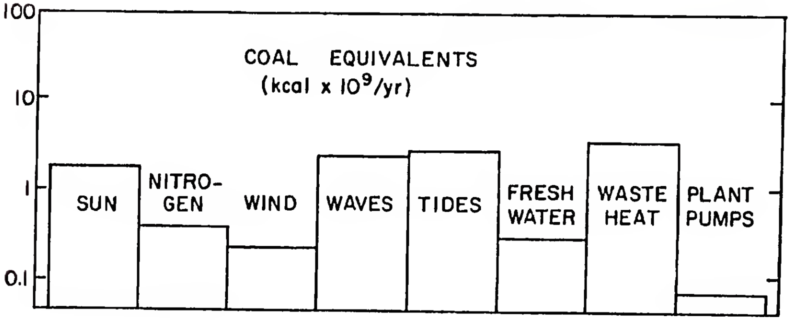
Figure 78. Energy signature for estuarine ecosystems at Crystal River. (a) Energy diagram illustrating interaction of eight important forcing functions contributing to system structure. (b) Energy signature of these external factors with values given in heat equivalent units. (c) Energy signature of same factors with values given in coal equivalent units. GPP indicates gross primary production.


TIDES
WASTE HEAT
PLANT PUMPS
NITRO-GEN
WIND
WAVES
FRESH WATER
STRUCTURE
SUN

(a)


HEAT EQUIVALENTS
(kcal x 10⁹/yr)
1000
100
10
1
0.1
SUN
NITRO-GEN
WIND
WAVES
TIDES
FRESH WATER
WASTE HEAT
PLANT PUMPS

(b)


COAL EQUIVALENTS
(kcal x 10⁹/yr)
100
10
1
0.1
SUN
NITRO-GEN
WIND
WAVES
TIDES
FRESH WATER
WASTE HEAT
PLANT PUMPS

(c)

Footnotes to Fig. 78.

Dimensions of Area Considered:

Area, $A = L \times W = (1.5\ \text{km})(1.5\ \text{km}) = 2.25\ \text{km}^2$

Sunlight:

$P_S = (4300\ \text{kcal/m}^2\text{-day})(365\ \text{days/yr})(2.25 \times 10^3\ \text{m}^2)$ (NOAA, 1963-74)

$= 3531 \times 10^9\ \text{kcal/yr}$ (heat equivalents)

$P_S = (3531 \times 10^9)/2000$ sun: coal $= 1.77 \times 10^9\ \text{kcal/yr}$ (coal equiv.)

Inorganic Nitrogen Influx:

Tidal exchange $= (2.25 \times 10^6\ \text{m}^2)(1.00\ \text{m})(2/\text{day}) = 4.52 \times 10^6\ \text{m}^3/\text{day}$

N-concentration $= 0.0665\ \text{g/m}^3$ (mostly nitrate)

Energy of oxidation for nitrate = 1.1 kcal/g N (E.P. Odum, 1971)

$P_N = (4.52 \times 10^6\ \text{m}^3/\text{day})(365\ \text{day/yr})(.0665\ \text{g/m}^3)(1.1\ \text{kcal/g})$

$= 0.12 \times 10^9\ \text{kcal/yr}$

C/N ratio for phytoplankton = 16/106 = 0.15 (Redfield, 1958)

Assume 10 kcal/g C (E.P. Odum, 1971)

Therefore 1 g N = 66.3 kcal

Assuming nitrogen is limiting factor,

$P_N = (0.665\ \text{g/m}^3)(66.3\ \text{kcal/g N})(4.52 \times 10^6\ \text{m}^3/\text{day})(365\ \text{day/yr})$

$= 7.27 \times 10^9\ \text{kcal/yr}/20$ productivity: coal (heat equivalent)

$= 0.36 \times 10^9\ \text{kcal/yr}$ (coal equivalents)

Wind:

Speed, $V = 8.5\ \text{kt} = 433\ \text{cm/sec}$

Assume eddy diffusion coeff., $C_e = 10^4\ \text{cm}^2/\text{sec}$

@ height $d = 10^4\ \text{cm}$

$P_S = 1/2\ \rho V^2 A C_e / d$

Footnotes to Fig 78. (Continued)

$= 1/2\ (1.2 \times 10^{-3}\ g/cm^3)(433\ cm/sec)^2(10^4\ cm^2/sec)(2.25 \times 10^{10}\ cm^2)$

$\times\ (2.39 \times 10^{-11}\ kcal/erg)(3.15 \times 10^7\ sec/yr)(10^{-4}\ cm^{-1})$

$= 1.91 \times 10^9$ kcal/yr (heat equivalents)

$= 0.19 \times 10^9$ kcal/yr (coal equivalents)

Waves:

Breaker height, H = 30 cm (Walton, 1973)

$P_W = 1/8\ \rho g^{3/2} \cdot H^{5/2} \cdot L = 1/8\ (1.025\ g/cm^3)(980\ cm/sec^2)^{3/2}(30\ cm)^{5/2}$

$\times\ (1.5 \times 10^5\ cm)(2.38 \times 10^{-11}\ kcal/erg)(3.15 \times 10^7\ sec/yr)$

$= 2.18 \times 10^9$ kcal/yr (heat equivalents)

$= 2.62 \times 10^9$ kcal/yr (coal equivalents)

Tides:

Range, h = 100.6 cm (NOAA, 1973)

$P_T = 1/2\ \rho g h^2 = 1/2(1.025\ g/cm^3)(980\ cm/sec^2)(2.25 \times 10^{10}\ cm^2/tide)$

$\times\ (100.6\ cm)^2(2.38 \times 10^{-11}\ kcal/erg)(705\ tides/yr)$

$= 1.9 \times 10^9$ kcal/yr (heat equvialents)

$= 2.7 \times 10^9$ kcal/yr (coal equivalents)

Freshwater:

Salinity of Inner Coastal Water - 24 o/oo (Smith, 1976)

Salinity of Outer Coastal Water - 29 o/oo (McKellar, 1975)

Tidal exchange, $V = 5.5 \times 10^6\ m^3/day$ (McKellar, 1975)

$P_F = \Delta G(V)(M_S) = (nRT\ LnC_1/C_2)\ V\ (M_S)$

$= (1/35)(1.99 \times 10^{-3})(293)\ \ln\ (24/29)(5.5 \times 10^6\ m^3/yr)(5{,}000\ g/m^3)$

$= 0.087 \times 10^9$ kcal/yr (heat equivalents)

$= 0.269 \times 10^9$ kcal/yr (coal equivalents)

Footnotes to Fig. 78. (Continued)

Waste Heat Discharge:

Assume only 1°C T from waste heat is available in unit area

Power plant flow, $Q = 3.5 \times 10^6 \ m^3/day$

C = specific heat of water = 1 cal/g°C

$P_D = \rho\ C\ Q\ \Delta T = (1.025\ g/cm^3)(10^{-3}\ kcal/g°C)(3.5 \times 10^{12}\ cm^3)$

(heat) $\times\ (365\ days/yr)(1°C)$

$= 1309 \times 10^9$ (heat equivalents)

$P_D = \rho\ C\ Q\ \Delta T^2/T = (1309 \times 10^9)(1°/293°)$

(coal) $= 4.47 \times 10^9$ (coal equivalents)

Power Plant Pumping:

Maximum Speed, v = 50 cm/sec

Plant flow, $Q = 3.5 \times 10^6 \ m^3/day$

$P_P = 1/2\ \rho\ Q\ v^2$

$= 1/2(1.025\ g/cm^3)(3.5 \times 10^{12}\ cm^3/day)(365\ day/yr)(50\ cm/sec)^2$

$\times\ (2.38 \times 10^{-11}\ kcal/erg)$

$= 0.039 \times 10^9$ kcal/yr (heat equivalents)

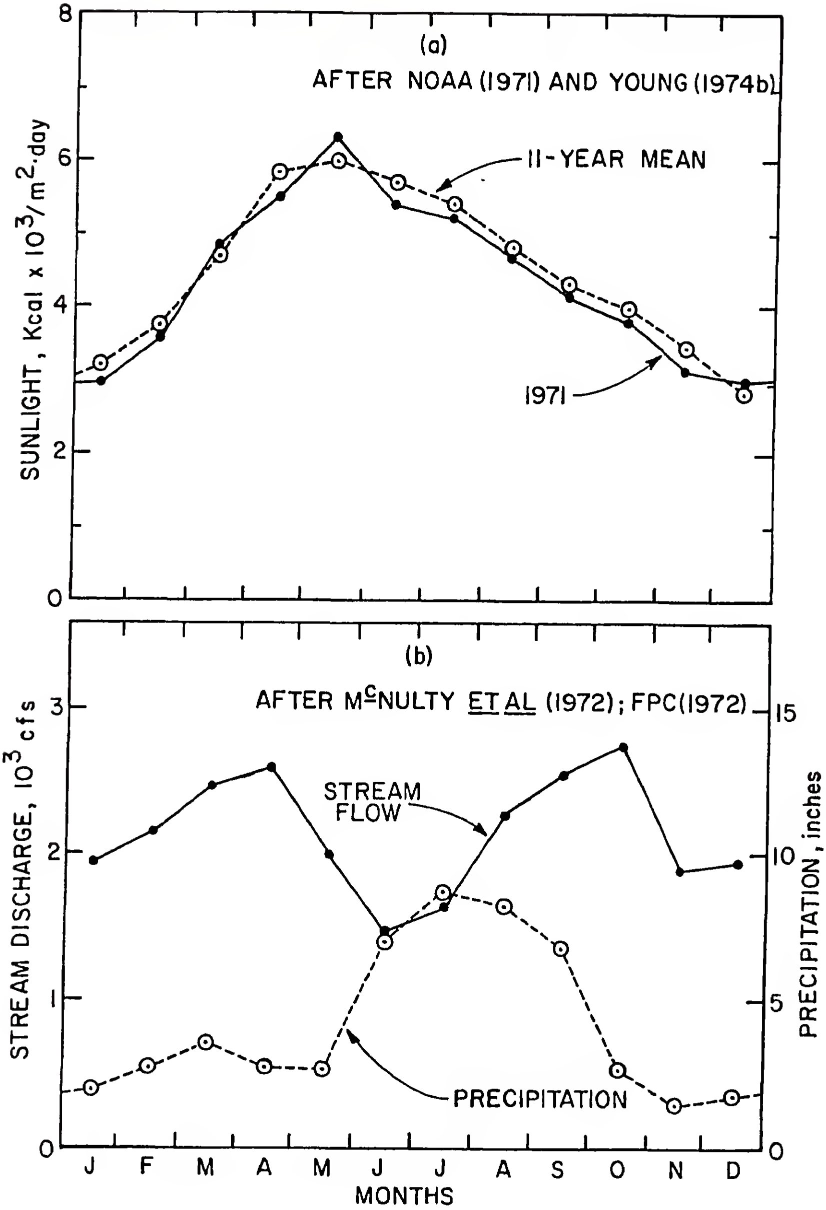
$= 0.066 \times 10^9$ kcal/yr (coal equivalents) bays studied by Smith (1976) and McKellar (1975). Relative magnitudes of the various energies influencing this estuary are shown in Fig. 78b in units of their inherent heat value (heat equivalents). Insolation constributes substantial heat kilocalories to the system's energy budget, as does the thermal energy of waste discharges from the power plant. Wind, waves and tides impart fewer heat equivalent kilocalories to the estuary, while nitrogen and fresh water inputs, as well as kinetic energy from the power plant are an order-of-magnitude less than the heat calories of wind, waves and tides.

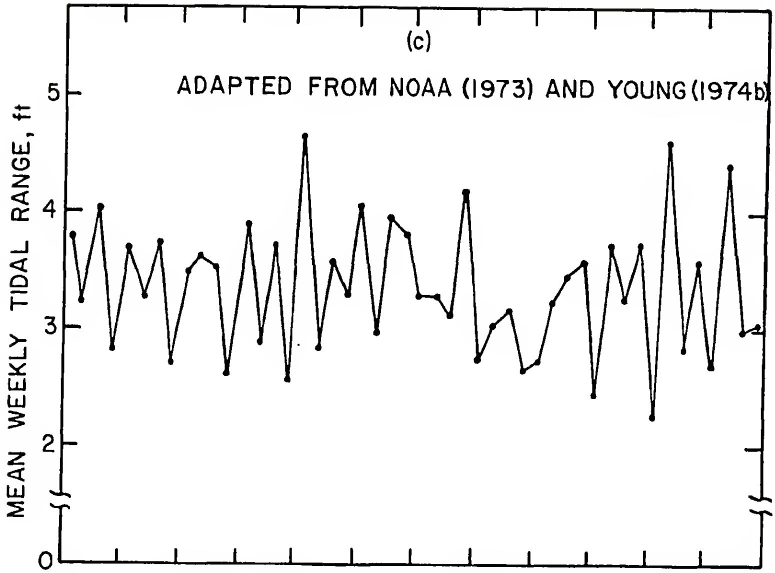
Energy quality ratios (Table 5) were applied to these data to indicate the comparative energy costs and the potential of these energies for doing work (compared to coal) in the estuarine system. When converted, the energy signature was changed in form (Fig. 78c). In this portrayal the disparity between quantities of different natural energies is reduced (from 5 orders-of-magnitude in Fig. 78b to slightly more than 1 in Fig. 78c). The relatively high quality energies of waves and tide match-up with the abundant chemical free-energy of freshwater, and these appear to be the dominant energy inputs to this ecosystem. This second version of the estuary's energy signature may be more relevant to the issue of relating external energies to internal system structure, since it is hypothesized (Odum, 1974b) that coal equivalents indicate ability of external energy to control and generate work.

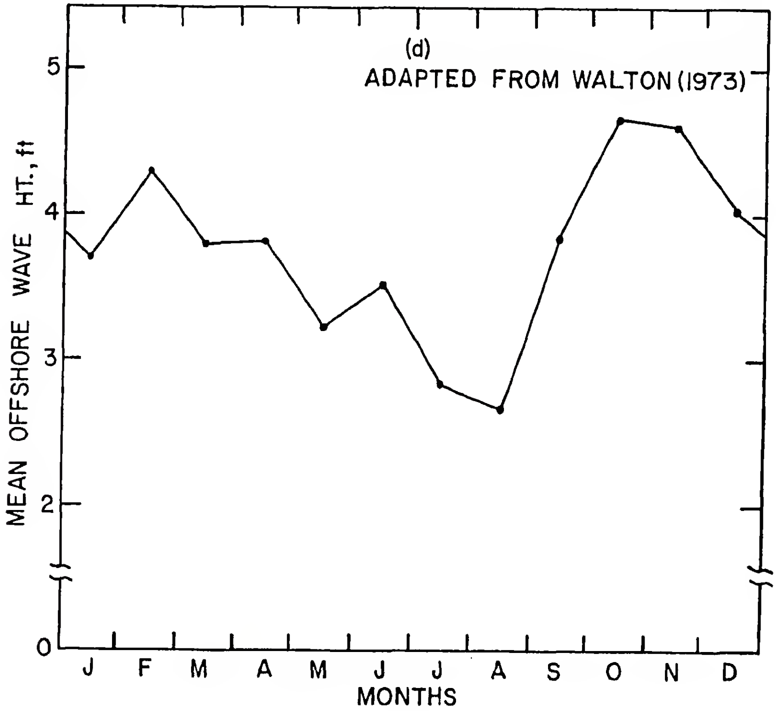
One way to synoptically examine the compatibility of this estuary with the power plant is to compare natural and fossil-fuel-based energy inputs to the estuary. Assuming that the various energies of nature are integrated in community productivity, a ratio of the power plant's thermal plus kinetic energies to the estuarine gross productivity may serve as an index for this comparison. At Crystal River this ratio was 4.5/1.8 = 2.5 (see footnotes to Fig. 78), suggesting that the balance between fossil fuels and natural energies in the estuary was about the same as it was for the U.S. in general. This is similar to the relationship estimated by Boynton (1975) for an oyster fishery in Florida, and it may indicate that the Crystal River estuary is not overloaded by power plant wastes.

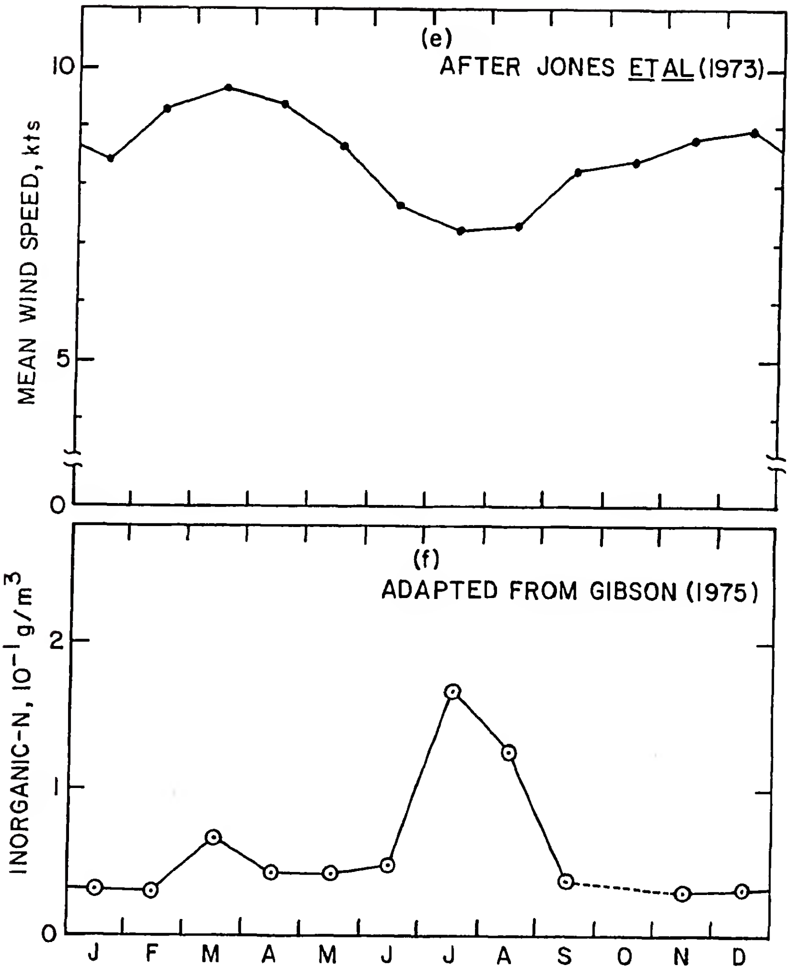
Annual cycles of the forcing functions which comprise the energy signature developed in Fig. 78 are given in Fig. 79. This information brings the "signature" into finer resolution, so that seasonal timing of peaks and troughs for each energy type can be examined. Those energies which have the most direct connection to estuarine biological processes (sunlight, temperature, and nutrients) exhibit late spring and summer maxima in unison. Since each is a potential limiting factor for ecosystem production this is fortuitous timing, indeed. River flow, wind and wave energies all show bimodal annual patterns with peaks in winter and fall. These energies are largely involved in transport phenomena moving imports into the system in the winter, before the major growing season and exporting product materials in the fall following the die-off. These energies interact in different stages of the same processes (e.g., sediment transport), and their synchrony may be more than coincidental. The way that different types of energy are coupled seems to be one that helps maintain high productivity. Tides are a dominant force throughout the year. There is very little difference in mean tidal ranges from season to season, and the pulsing nature of tidal energies may contribute to net productive processes in the estuary (H.T. Odum, 1971; Boynton, 1975). The potential energy of

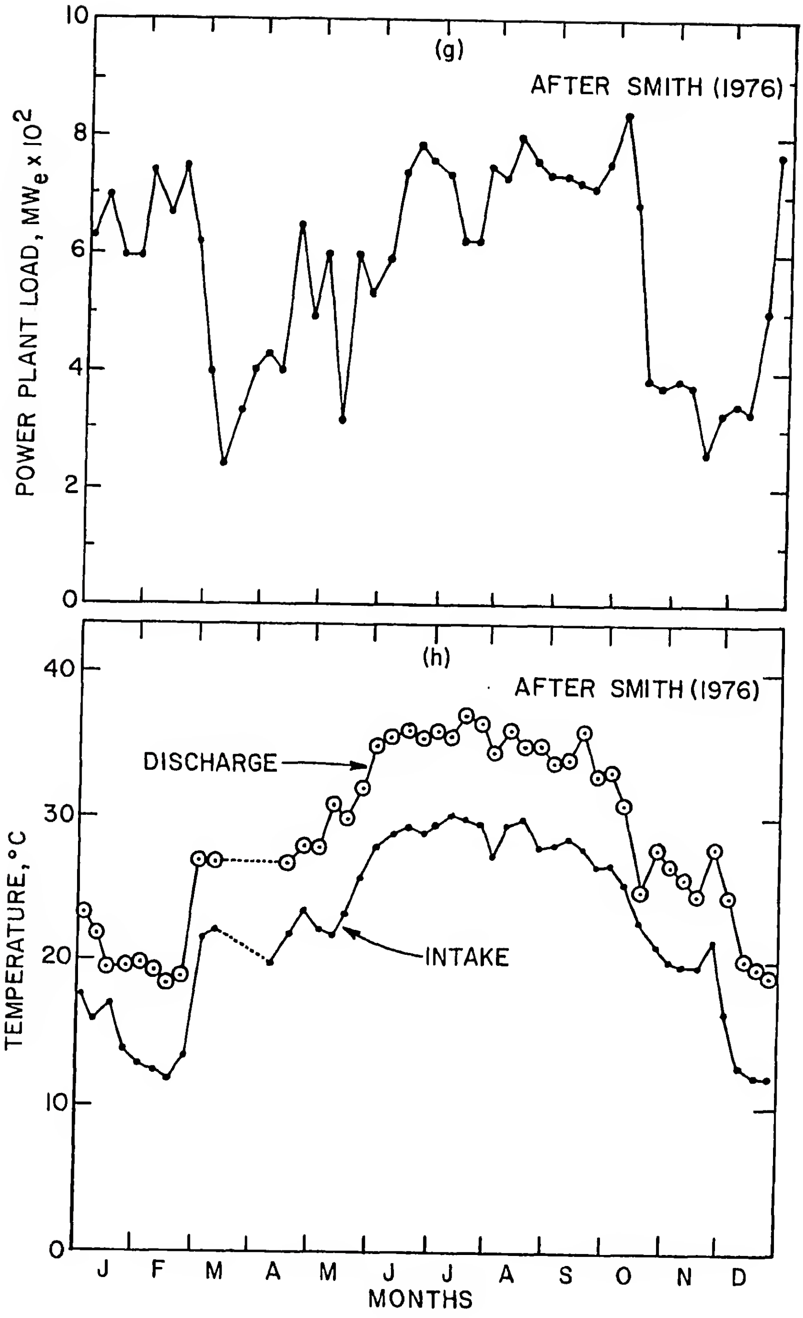
Figure 79. Annual cycles of forcing functions which comprise the energy signature for Crystal River estuary given in Fig. 14: (a) Solar radiation for 1971 and for the mean of 11 years (1961-1971) at Tampa, Fla.; (b) Monthly rainfall for 1971 and combined stream flow for Withlacoochee R. and Crystal R. in 1971; (c) Weekly mean tidal range for 1973; (d) Mean offshore wave height for Gulf of Mexico near Florida's northwest; (e) Monthly mean wind speed for 1972; (f) Total inorganic nitrogen concentration at outer coastal station in 1973; (g) Power plant generating load and intake and discharge water temperatures for 1973-74.


(a)
AFTER NOAA (1971) AND YOUNG (1974b)
11-YEAR MEAN
1971
SUNLIGHT, Kcal x 10^3/m^2·day
0
2
4
6
8
(b)
AFTER McNULTY ET AL (1972); FPC(1972)
STREAM FLOW
PRECIPITATION
STREAM DISCHARGE, 10^3 cfs
0
1
2
3
PRECIPITATION, inches
0
5
10
15
J
F
M
A
M
J
J
A
S
O
N
D
MONTHS


(c)
ADAPTED FROM NOAA (1973) AND YOUNG (1974b)
MEAN WEEKLY TIDAL RANGE, ft
0
2
3
4
5


(d)
ADAPTED FROM WALTON (1973)
MEAN OFFSHORE WAVE HT., ft
0
2
3
4
5
J
F
M
A
M
J
J
A
S
O
N
D
MONTHS


(e)
AFTER JONES ET AL (1973)
MEAN WIND SPEED, kts
10
5
0
(f)
ADAPTED FROM GIBSON (1975)
INORGANIC-N, 10^{-1} g/m^3
2
1
0
J
F
M
A
M
J
J
A
S
O
N
D


(g)
AFTER SMITH (1976)
POWER PLANT LOAD, $MW_e \times 10^2$
0
2
4
6
8
10
(h)
AFTER SMITH (1976)
DISCHARGE
INTAKE
TEMPERATURE, °C
0
10
20
30
40
J
F
M
A
M
J
J
A
S
O
N
D
MONTHS

power plant thermal wastes is indicated by the difference between intake and discharge temperatures (Fig. 79h), and this ΔT is greatest in mid-summer and mid-winter periods when power plant loading rate is at its maximum. The mean plant load for 1973 was 578 MWE, which was only 64% of power plant capacity.

Recommended Procedure for Energy Analysis of Environmental Impacts

In the present study, changes in estuarine ecosystems resulting from power plant operation were evaluated in energy units of the same quality. Manifold ecological impacts were considered, including: changes in primary productivity, direct mortalities inflicted on estuarine animals and changes in coastal hydrodynamics. A few other studies considering environmental impacts of power plants have attempted to evaluate these kinds of impacts in monetary (or other) terms.

For the Millstone nuclear power station in Connecticut (AEC, 1973b), mortalities of plankton by entrainment were evaluated on an "average-fish-it-would-support" basis, where (for instance) 100 kg of zooplankton was taken as equivalent to 1 kg of fish. Fish were given an average economic value approximately equal to dockside cost of "industrial fish" (DMR, 1963-73). This relationship between plankton and fish is conceptually much the same as the method for calculating energy qualities of animals in an estuarine food web employed in this dissertation. Similar equivalences between plankton and fish production also have been suggested by others (including: Hellier, 1962; McFarland, 1963; Ryther, 1969; Isard et al., 1972). Dahlberg (1977) and AEC (1973a) have attempted to estimate the value of meroplankton as potential adult organisms by applying "natural survival" rates in a manner similar to that used in this dissertation. However, they only considered the commercially important species in their analysis, although in AEC (1973a) all fish were given at least minimal commercial importance as "industrial fish."

Thus, it can be seen that several other efforts have been made to evaluate some of the diverse environmental impacts of power plants in equivalent, objective units of measure. However, these previous evaluations have not been comprehensive in scope, nor have they been integrated into a general theory of value. The following seven fundamental steps for an environmental evaluation procedure are given to illustrate the general nature of energy evaluations used in this study. This outline may be considered a basic rationale pertinent to any environmental evaluation issues.

1) The first step is conceptualization of models for describing the problem. Models serve as formal definitions of the problem, as formats for data organization, and eventually, as tools for predicting the behavior of particular systems under various contingencies (step 5).

2) Next, alternative plans need to be selected. In this study government regulatory agencies had suggested the possible need for closed-cycle cooling, and Gilbert Associates (1974) selected the 6 most feasible methods for achieving a so-called closed-cycle cooling system.

3) Thirdly, an objective function must be defined. This amounts simply to a clear statement in words or mathematical terms (as in "operations research") of what the evaluation is going to try to accmplish. This may be the most fundamental but oft

ignored step in the overall procedure. In traditional quantitative planning, objective functions described in economic terms include: maximization of net economic output; maximization of economic efficiency; or redistribution of wealth. In energy analysis and environmental planning, the objective function is to maximize the net energy channeled into work processes in the region, where work includes both that of man and of nature.

4) The next step is to assemble and/or measure scientific data to describe the systems being evaluated. This step often comprises the bulk of this work in the evaluation process. The models which were developed to define the study ecosystems are used to direct the search and research for quantitative data. Models tell the planner where the major "holes" are in his understanding of the systems, so that emphasis can be placed on these weak points for data assembly.

5) Next, mathematical models are developed from the conceptual models of step number (1), and these are used for computer simulation of ecosystem behavior. Model coefficients are evaluated from a portion of the data developed in step (4) and normative model output is validated against other portions of this data. Reciprocally, sensitivity analysis of the system model indicates which parameters have greatest influence on overall model behavior, again suggesting important parameters to emphasize in the data compilation of step (4). These simulation models are the only objective tools available to the planner for forecasting what will be the effects of alternative plans on interacting ecosystems, before the alternative is

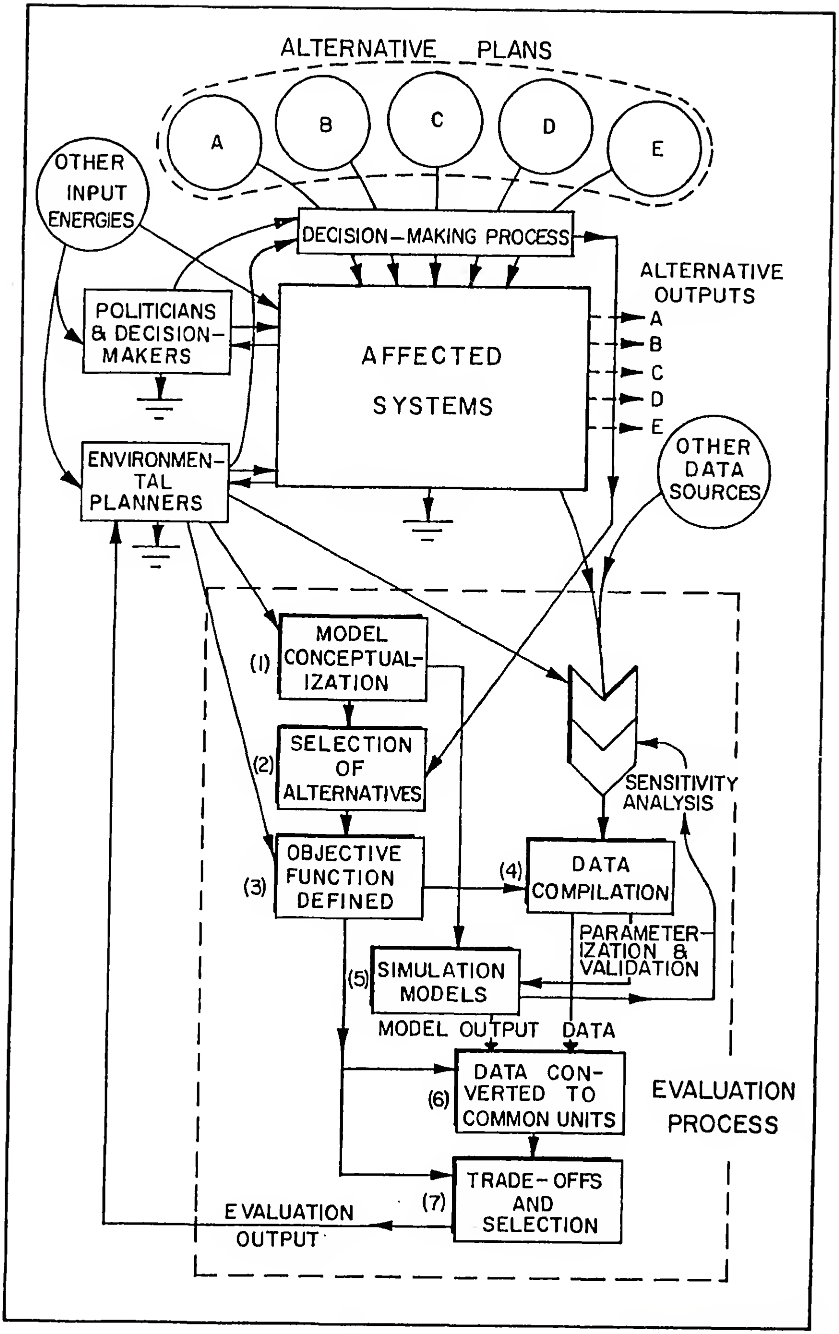
enacted.

6) Pertinent pieces of assembled data and model outputs are converted into some common units of measure for comparing the effects of management alternatives. Traditional procedures (as in step 3) attempt to convert alternative benefits and costs into monetary units, but market generated dollar values do not nearly measure the full benefits of natural systems to man. In the energy analysis techniques of Odum (1974a) as implemented in this study, data are put in energy terms that indicate the ability of a given system component to do work in the large scale system context.

7) Finally, the benefits and costs of alternative plans are calculated (in energy terms) and the tradeoffs are estimated quantitatively for the decision-makers. The plan which best fulfills the objective function (step 3) is considered best by this evaluation procedure.

The general flow of events in an environmental evaluation procedure is depicted in Fig. 80. The information flows implicit in the above seven steps are aggregated together within the dashed-line rectangle, and these flows interface with the decision making process via the environmental planner. This environmental evaluation procedure as outlined here may be used to make scientific data available to planners, decision-makers and the general public in a digested, flexible and understandable format. The final decisions will most likely involve political factors as well. However, if society is to hold any hope for imparting the energetic, economic and ecological wisdom gleaned from scientific study into its resource management activities, planners

Figure 80. Generalized model of decision-making process suggested for environment evaluation.


ALTERNATIVE PLANS
A
B
C
D
E
OTHER INPUT ENERGIES
DECISION-MAKING PROCESS
ALTERNATIVE OUTPUTS
A
B
C
D
E
POLITICIANS & DECISION-MAKERS
AFFECTED SYSTEMS
ENVIRONMENTAL PLANNERS
OTHER DATA SOURCES
(1)
MODEL CONCEPTUALIZATION
(2)
SELECTION OF ALTERNATIVES
SENSITIVITY ANALYSIS
(3)
OBJECTIVE FUNCTION DEFINED
(4)
DATA COMPILATION
PARAMETERIZATION & VALIDATION
(5)
SIMULATION MODELS
MODEL OUTPUT
DATA
(6)
DATA CONVERTED TO COMMON UNITS
EVALUATION PROCESS
(7)
TRADE-OFFS AND SELECTION
EVALUATION OUTPUT

must utilize evaluation techniques which encourage feedback of scientific data into the political process.

Energy Basis for a Coastal Power Plant in its Regional Economy

The principal energy inputs and outputs characterizing the powershed region are summarized in the aggregated model of the regional system given as Fig. 81. Numbers are given to indicate the relative magnitudes of energy flows in units of trillion coal-equivalent kilocalories per year. The fossil-fuel-based energy flows across the system boundary (at the top) are generally greater than the renewable energy inflows from nature (on the left). However, terrestrial productivity contributes the second largest energy input to the region, accounting for 16 percent of the total flow. The combined input of electric and other fuels amounts to some 34 percent of the total flow.

In Table 44 the balance of energies supporting the Crystal River powershed is summarized and compared with the U.S., the State of Florida, and two smaller regions of Florida. Relative levels of development in a region are indicated by the "energy ratios" given in the table. The ratio of fossil-fuel-based energy inputs to the renewable energy resources of nature has been termed the "investment ratio" (Odum, 1976; Odum and Odum, 1976), and it is a measure of the relative level of development for a given regional economy. Regions with higher ratios are more developed than those with lower investment ratios. It may be important for the economy of a regional system to match the investment ratio of the strongest competing system. When the ratio is too high, products of the economic system cannot be sold at a

Figure 81. Energy diagram of regional study area (powershed) depicting energy-economic budget for 1973. Numbers represent energy value inputs and outputs for powershed given in kcal CE x 10^{12}/yr.

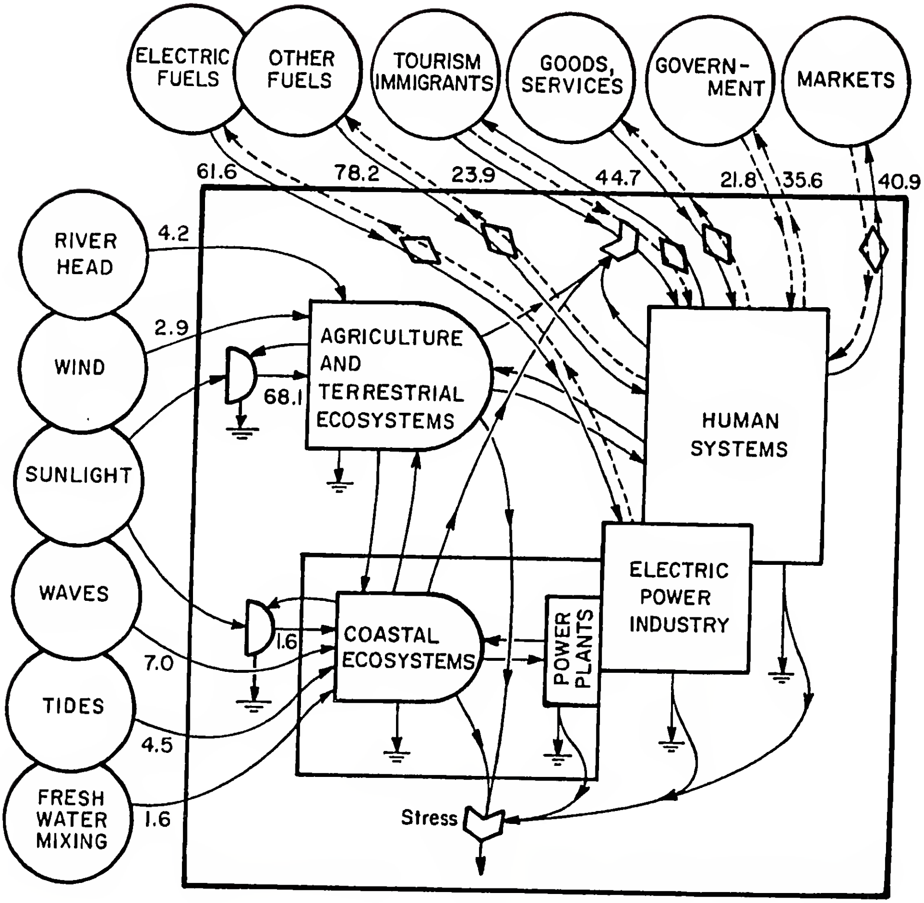

ELECTRIC FUELS
OTHER FUELS
TOURISM IMMIGRANTS
GOODS, SERVICES
GOVERN-MENT
MARKETS
61.6
78.2
23.9
44.7
21.8
35.6
40.9
RIVER HEAD
4.2
WIND
2.9
SUNLIGHT
68.1
AGRICULTURE AND TERRESTRIAL ECOSYSTEMS
HUMAN SYSTEMS
WAVES
1.6
7.0
TIDES
4.5
FRESH WATER MIXING
1.6
COASTAL ECOSYSTEMS
POWER PLANTS
ELECTRIC POWER INDUSTRY
Stress

Table 44. The balance of energies supporting regional systems: a comparison of the Crystal River powershed with the U.S., Florida and other regions.

Regional System	Energy Inputs, kcal CE x 10^{12}/yr			Energy Ratios	
	Fossil Fuels (F)[a]	Natural Energy (N)[b]	Power Plants (P)[c]	F/N	P/F
Crystal River Powershed[d]					
1973 Conditions	118.1	69.8	47.59	1.69	0.40
with Anclote #1	129.1	69.8	58.62	1.85	0.45
with Crystal River #3	146.5	69.8	76.02	2.10	0.52
Upper St. Jonhs[e]	20.9	13.2	7.5	1.58	0.55
Dade County[f]	73.6	12.1	38.7	6.08	0.53
Florida[g]	432.5	177.3	182.4	2.44	0.42
United States[h]	18,170.0	6,740.0	4,910.0	2.70	0.27

[a] Includes all fossil-fuel-based inputs minus outputs, except for U.S., Florida and Dade County data where only the actual fuels were considered.

[b] Includes only solar energy input as manifested in primary productivity.

[c] Includes both fossil and nuclear fuels used to generate electric power. For Dade County and Upper St. Johns, electricity consumption was tallied rather than electricity generation.

[d] Assumes no increase in fuel consumption except for power plant with additional units.

Table 44. (Continued)

[e] Upper part of St. Johns River Basin, Florida including Brevard County (Bayley et al., 1976a, b). Data for 1973.

[f] Study of Dade County, Florida from Zucchetto (1975a, b) for 1973.

[g] Fuel data for 1973 from Schrode et al. (1975). Natural energy estimated by assuming some productivity per unit land area as calculated for study region.

[h] Data from Kylstra (1974) and Smith (1975) for 1972.

competitive price because they were created with too little input of "free" energies from nature. When the ratio is too low, the economic system is not making adequate use of its natural resources to attract economic investment.

The investment ratio for the powershed was found to be low (1.69) relative to Florida (2.44) and the U.S. (2.70). This matches our intuitive judgement of the study area as a "relatively rural" part of Florida; however, we now have a quantitative index of that relative condition, and in these energetic terms we can say that the powershed is only about 70% as developed as is Florida, in general and some 63% as developed as the U.S. An energy budget for the upper part of the St. John's River Basin indicated a similar level of development with a ratio of 1.5. In contrast, Zucchetto's (1975a and b) work for Dade County suggests a highly developed region with a ratio of about 6.1, or 3.6 times that of the Crystal River powershed. This ratio for Dade County may be slightly misleading, however, because it does not fully consider imports and exports of goods (with their particular energetic composition) other than fuels, and because of the artificially small boundary (county) defined for that study. In summary, by the criteria of the present analysis and for the static conditions of these calculations, the Florida Power Corporation powershed is less developed than the systems within which it must compete for markets and investments (i.e., Florida and U.S.). The questions of further development for power plant construction in this region must thus be considered on other criteria.

The percent investment in electric power industry of a region can be inferred from a ratio of fuels consumed for electric power generation to the total fuels consumed in that region. For convenience this can be called the "electric energy ratio," and it was calculated and tabulated for comparison of 5 regions in Table 44. Notice first that this electric energy ratio is almost 56 percent higher for Florida than for the U.S. average. This may be attributable to the extensive use of air conditioners in Florida and the limited use of space heating fuels for the short Florida winters. In Florida approximately 6.3% of the state's total fossil fuel consumption is used for air conditioning (Shrode et al., 1975). Therefore, assuming a coefficient of performance = 2.2 kcal cooling/kcal electricity (Anon., 1973), for every kcal of air conditioning in the powershed, there would be 8 kcal of electricity generated at the Crystal River (or other) power plant and 13 kcal of waste heat to the estuary (or other water body).

In 1973 the powershed was characterized by an electric energy ratio 5% lower than the Florida average but still about 50% greater than the U.S. mean. Footnote (a) to Table 10 indicates that substantial ~~44~~ 10
electricity was probably imported to the region during that year. To compensate for this and to meet growth projections, Florida Power Corporation constructed Anclote unit #1 and Crystal River unit #3. As indicated in Fig. 18 (a and b), however, the rate of fossil fuel supported growth appears to have slowed substantially in Florida since 1973. The energy balance for the powershed was investigated for two additional conditions: (1) operation of Anclote unit #1; (2) operation of Crystal River unit #3. For both cases the analysis is made assuming that the only additional fuel into the region is that needed to operate the power plants. With the addition of Anclote #1 the electric energy ratio for the region, calculated in Table 44, has grown in slight excess

of the 1973 ratio for Florida, and the addition of Crystal River #3 increases this ratio to 24 percent higher than the 1973 Florida ratio. This energy analysis, therefore, indicates that some caution should be taken in planning the expansion of electric power generation for the Crystal River region, until such time as the rest of the economy matches the power industry in energy consumption.

CONCLUSIONS

In conclusion the following points are noted.

(1) The energy evaluation procedure used in this study is an objective methodology having general utility for environmental planning.

(2) The energy base for the Crystal River powershed was characterized by about 1.9 times as much energy contributed from fossil fuels as from natural (solar-based) sources. The ratio of fossil fuels to natural energy inputs for this region was about 30% lower than the national average, indicating the region to be relatively undeveloped. However, the proportion of fossil fuels invested in electric power generation in the powershed was 67% higher than the national average and 7% higher than the Florida average. Thus, there has been extravagant investment in power plants for this region, possibly in anticipation of further economic development.

(3) The Crystal River power plant has had diverse influences on adjacent estuarine ecosystems. The major areas of impact included entrainment mortalities inflicted on meroplankton and juvenile fish, as well as inhibition of productivity in the ecosystems receiving power plant discharges. The total annual cost to the estuaries and region resulting from power plant operation amounted to some 5.3×10^9 kcal CE/yr (equivalent to about $256,000/yr), while the ecological impact of plant construction alone was about 2.4×10^9 kcal CE/yr.

(4) A simulation of model of the estuarine ecosystems receiving thermal wastes was used to predict the effects of adding a third power plant generating unit. A parabolic relationship between temperature and productivity, derived as a simplification of theoretically based function, produced model behavior which closely matched field data. It was estimated that the ecological effects of a 3-unit power plant would be almost 80% greater than for the 2-unit plant. The total predicted impact would be equivalent to about $690,000/yr.

(5) A model was developed to describe generalized functional relationships between trophic levels in an estuarine ecosystem at Crystal River. The model was derived from detailed data on stocks and energy flows in the trophic web of a saltmarsh creek ecosystem, and it was used to determine the amount of gross primary productivity needed to support a unit of secondary production at each trophic level. For example, about 20 kilocalories of gross productivity would be needed per kilocalorie of mullet (Mugil cephalus) production, while a kilocalorie of production by crevalle jack (Caranx hippos) would require almost 300 kilocalories of gross productivity. This information was used to relate power plant effects on tophicaly higher organisms to effects on primary productivity.

(6) The costs of using technological measures to ameliorate these ecological impacts of power plant operation were examined. The cheapest closed-cycle cooling systems for a 3-unit power plant were multi-cell mechanical draft towers and modular spray units, ranging

around \$17 x 10^6/yr (350×10^9 kcal CE/yr). This is about 25 times greater than the cost of ecological damage due to the power plant. Ecological effects of the cooling facilities themselves (salt spray and displacement of ecosystems) were estimated to be equivalent to about 1% of the economic cost of the facilities.

(7) The cooling water canals were observed to be viable interface ecosystems characterized by high productivities and large standing stocks of animals.

a. Gross primary productivities of the canals (annual mean = 7.8 g $O_2/m^2 \cdot$day) averaged about 33% higher than for the bay ecosystems and 50% lower than salt marsh productivity.

b. There was no statistical difference between productivities of the two canals, whereas the inner bay receiving power plant wastes was about 43% less productive than control ecosystems, possibly indicating that the discharge canal was relatively well adapted to thermal wastes.

c. The discharge canal served as a buffer zone, absorbing some of the stress of thermal wastes. Carbon-14 measurements of plankton photosynthesis indicated that productivities were generally lower at the point of discharge (sta. 5) than at intake stations. However, by the time the effluent had traveled to the end of the discharge canal (sta. 7), productivity values were 40-100% higher than at the point of discharge and had almost returned to levels measured at intake stations.

d. Benthic communities of the discharge canal generally had lower diversity (17.2 spp/1000 individuals) but similar standing stocks (31.2 g organic matter/m^2) compared to the intake canal. Benthic biomass in the canals was 3-6 times greater than for the benthic communities in the bays at Crystal River. Standing stocks of oysters were 2.4 times higher in the discharge canal than in the intake, even though spat set in the discharge was reduced by over 90%.

e. Standing stocks of nekton in the canal ecosystems (3.2 g dry matter/m^2) were more than twice as high as those measured in the bays.

f. Measurements of standing stocks, migration and impingement of nekton in the intake canal indicated that about 15-25% of the batfish and blue crab stocks killed on the power plant intake screens were produced within the canal ecosystem. Generally, however, immigration of nekton replaced the canal populations at a rate of 1-3 times per year, and for most species the canal serves only as a channel carrying fish to the power plant.

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APPENDIX A

Species composition and distribution for major plant communities in the canal ecosystems at Crystal River.

Table A1. Summary of dominant benthic plant species encountered in canals at Crystal River power plant for samples taken on 8 February and 25 June 1975.[a]

Location (depth)	Community Type	Species	Relative Abundance[b]
Intake Canal Littoral (0-2 m)	Mat	Cyanophyta	
		Entophysalis deusta	D
		Lyngbya semiplena	A
		Schizothrix rivularis	D
		S. calcicola	C
		Chrysophyta	
		Pleurosigma sp.	C
		Synedra sp.	C
		Vaucheria sp.	C
Mid-Depth[c] (2-4 m)	Macrophytes	Seagrasses	
		Halodule beaudettei	A
		Halophila engelmanil	C
		Chlorophyta	
		Caulerpa prolifera	C
		C. cuppressaides	C
		C. paspaloides	A
		C. ashmeadii	C
		Rhodophyta	
		Gracilaria sp.	A
		Laurencia sp.	C
		Phaeophyta	
		Sargassum sp.	D
		Dictyota sp.	C

Table A1. (Continued)

Location (depth)	Community Type	Species	Relative Abundance[b]
Intake Canal Deep (3-5 m)	Ephiphytes		
		Centrocerus sp.	A
		Chrysophyta	
		Pleurosigma sp.	C
		(*cf. Meridion sp.*)	C
Discharge Canal Upper Littoral (0-1 m)	Mat	Cyanophyta	
		Lyngbya confervoides	C
		Oscillatoria geminata	A
		Schizothrix sp.	A
		Arthrospira sp.	C
Mid-Littoral (0.5-1.5 m)	Mat	Cyanophyta	
		L. confervoides	A
		L. semiplena	C
		O. geminata	A
		Schizothrix sp.	C
		Microcoleus tenerrimus	C
		M. chthonoplastes	A
		Entrophysalis sp.	C
		Chrysophyta	
		Vaucheria sp.	A
Lower Littoral (1-2 m)	Mat	Cyanophyta	
		M. chthonoplastes	C
		L. confervoides	A
		L. semiplana	C
		O. geminata	C
		O. amphibia	C
		Chrysophyta	
		Vaucheria sp.	D

Table A1. (Continued)

Location (depth)	Community Type	Species	Relative Abundance[b]
Discharge Canal Sub-Littoral (2-3 m)	Mat & Macrophyte	Cyanophyta *L. confervoides*	A
		Polysiphonia denudata	C
		Chlorophyta *Enteromorpha flexuosa*	A
		Rhodophyta *Erythrotrichia carrea*	A
Deep (3-4 m)	Tufted colonies	Rhodophyta *Wranglia sp.*	D
		Cyanophyta *P. denudata*	C
		Chrysophyta (*cf. Nitschia sp.*)	C
		(*cf. Meridion sp.*)	C

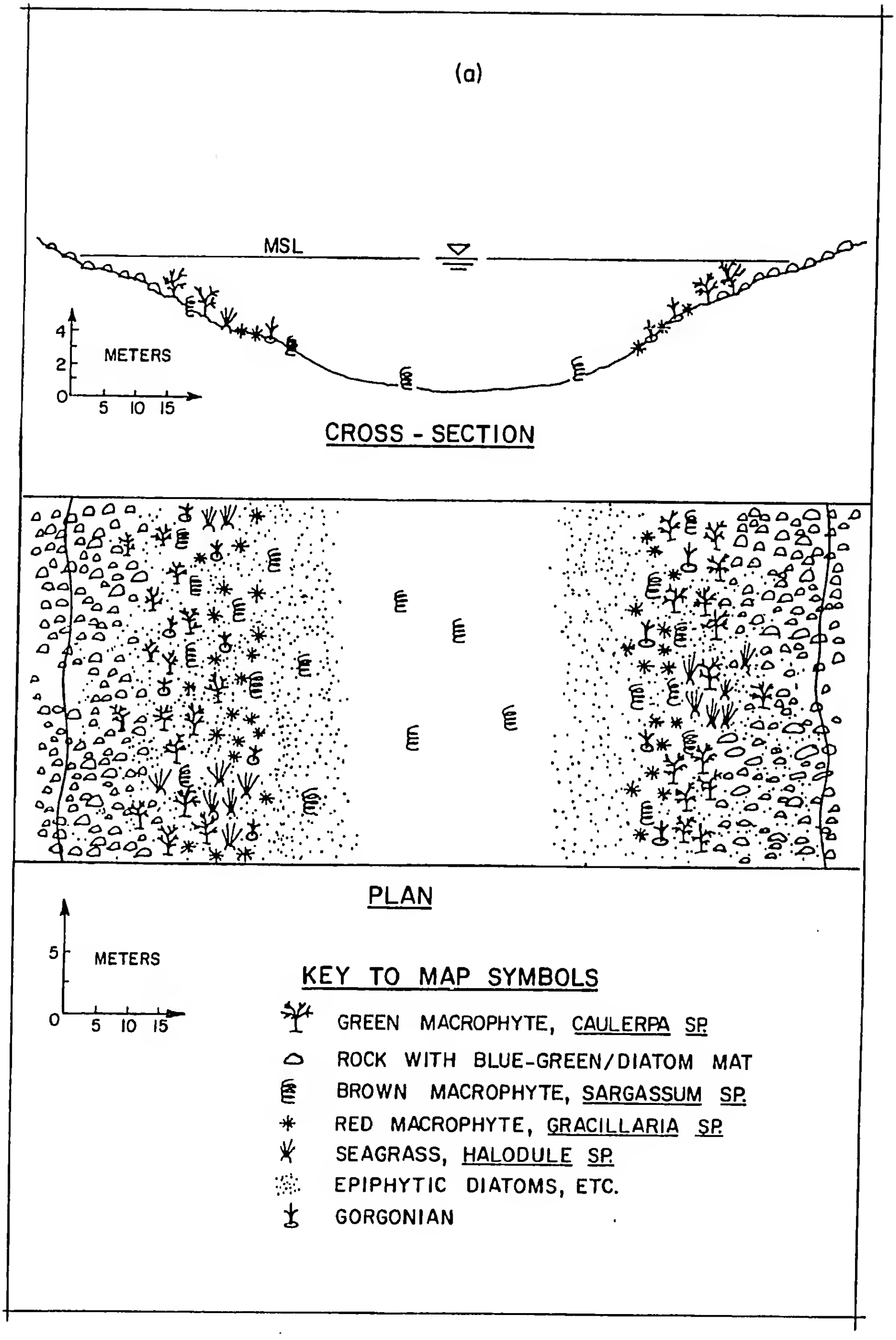
---

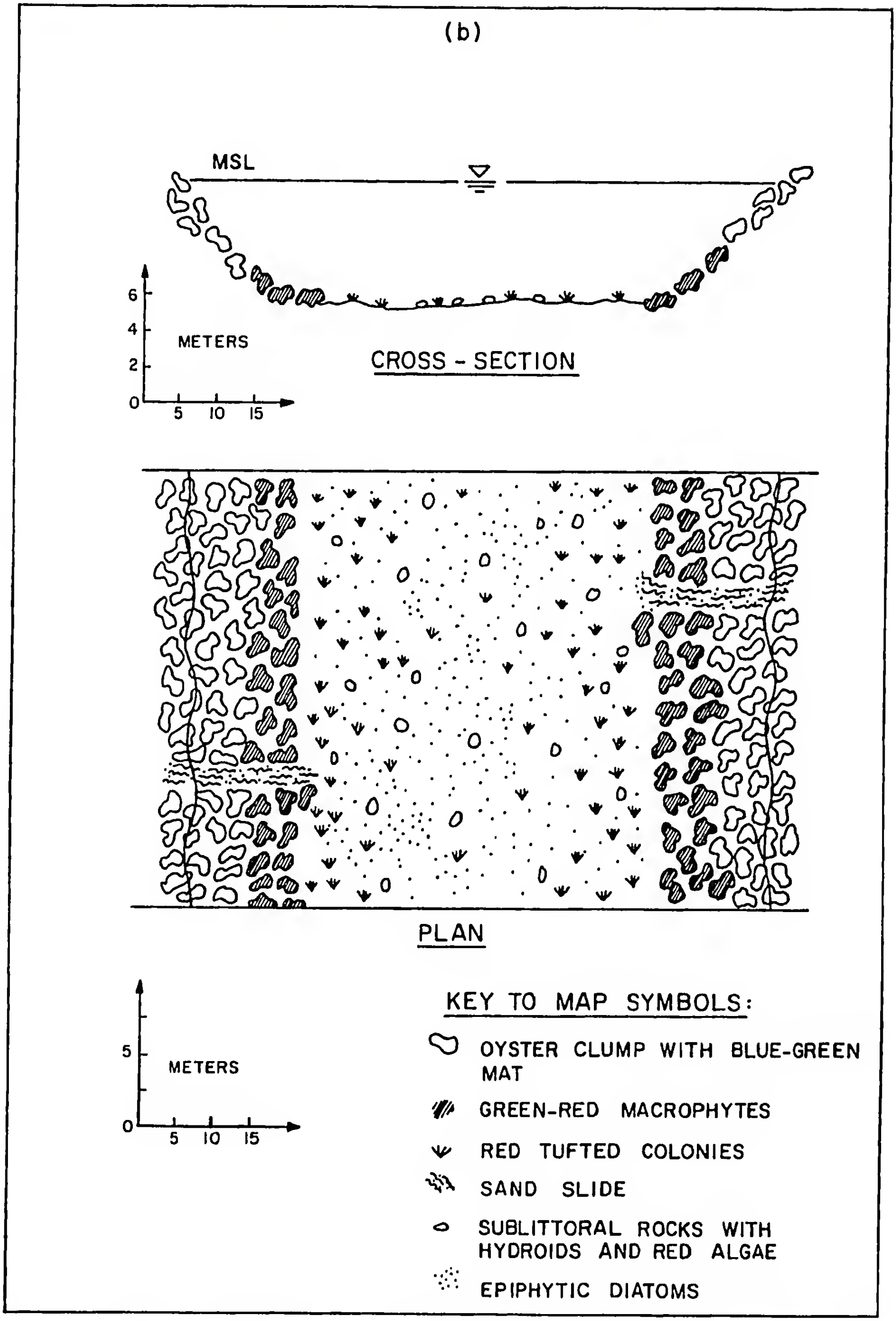
[a] Samples were collected by SCUBA and were identified with the assistance of M. Frank. Approximately 100 m lengths of intake canal at three locations (near sta. 2, 2A and 3) and about 75 m lengths of discharge canal at two locations (near sta. 5 and 6) were sampled.

[b] Subjective measure of relative abundance, where D = dominant, A = abundant, C = common.

[c] This zone also contained epiphytes as in the deeper (3-5 m) zone.

Figure A1. Spatial distribution of major plant communities in the (a) intake canal and (b) discharge canal ecosystems at Crystal River. Diagrams are composites of SCUBA observations made on 8 February and 25 June, 1975, at stations 2, 2A and 3 of intake canal and stations 5 and 6 of discharge canal. No substantial qualitative changes were observed between sampling dates or between stations in either canal.


(a)
MSL
4
2
0
METERS
5
10
15
CROSS - SECTION
PLAN
5
METERS
0
5
10
15
KEY TO MAP SYMBOLS
GREEN MACROPHYTE, CAULERPA SP.
ROCK WITH BLUE-GREEN/DIATOM MAT
BROWN MACROPHYTE, SARGASSUM SP.
RED MACROPHYTE, GRACILLARIA SP.
SEAGRASS, HALODULE SP.
EPIPHYTIC DIATOMS, ETC.
GORGONIAN


(b)
MSL
6
4
2
0
METERS
5
10
15
CROSS - SECTION
PLAN
5
METERS
0
5
10
15
KEY TO MAP SYMBOLS:
OYSTER CLUMP WITH BLUE-GREEN MAT
GREEN-RED MACROPHYTES
RED TUFTED COLONIES
SAND SLIDE
SUBLITTORAL ROCKS WITH HYDROIDS AND RED ALGAE
EPIPHYTIC DIATOMS

APPENDIX B

Detailed data to describe the benthic animal communities in the canal ecosystems at Crystal River.

Table B1. List of benthic marine animal species collected in canals at Crystal River power plant, 1974-1975.

Phylum	Organism	Common Name	Occurrence[1]	
			Intake	Discharge
Porifera				
Class Demospongiae	*Cliona sp.*	Boring sponge	+++	+++
	Haliclona sp.	Encrusting sponge	++	+++
Cnidaria				
Class Anthozoa	(*cf. Aiptasiomorpha sp.*)	Sea anemone	+	+
Class Hydrazoa	*Campanularia sp.*	Hydroid	++	++
Platyhelminthes				
Class Turbellaria	Unidentified Polycladida	Flatworm	+	
Nemertea	Unidentified Nemertean	Ribbon worm	+	
Sipuncluloidea	Unidentified Sipunculid	Gephyrean	+	
Annelida				
Class Polychaeta				
Arabellidae	*Arabella iricolor*	---	++	
Arenicolidae	*Arenicola sp.*	Lug worm	+	
Eunicidae	*Marphysa sp.* A	---	++	+++
	Marphysa sp. B	---	+	++

Table B1. (Continued)

Phylum	Organism	Common Name	Occurrence[1]	
			Intake	Discharge
Flabelligeridae	(cf. *Stylaroides sp.*)	---	+	
Nereidae	*Nereis sp.*	Clam worm	+	+++
	Perinereis sp.	---	+	
	Neanthes sp.	---	+	+
Polynoidae	*Lepidonotus variabilis*	Scale worm	+	+
Serpulidae	*Spirorbis sp.*	Tube worm		+
	Unidentified Serpulid	Tube worm	+++	+++
Terebellidae	Unidentified Terebellid	Hydra-worm		+
Arthropoda Class Pycnogonida	Unidentified Pycnogonid	Sea spider	+	
Class Crustacea Subclass Cirripedia	*Balanus eburneus*	Ivory barnacle	+++	++++
	Balanus improvesus	Acorn barnacle	+++	++++
	Balanus amphitrite	Striped barnacle	++	+
Order Isopoda	Unidentified Isopod A	Sea bug		+
	Unidentified Isopod B	Sea bug	+	+

Table B1. (Continued)

Phylum	Organism	Common Name	Occurrence[1]	
			Intake	Discharge
	Ligia sp.[2]	Rock slater	++	++
Order Amphipoda	Unidentified *Gammarid* A	Scud	+	+
	Unidentified *Gammarid* B	Scud	+	
	Unidentified *Caprellid*	Skeleton shrimp	+	
Order Decapoda	*Alpheus heterochaeolis*	Snapping shrimp	++	+
	Upogebia affinis	Mud shrimp	++	+
	Eurypanopeus depressus	Mud crab	+++	++++
	Eurypanopeus abbreviatus	Mud crab	+++	++++
	Panopeus herbsti	Mud crab	+++	++++
	Calinectes sapidus[2]	Blue crab	+	+
	Pinnixia christata	Oyster crab	+	
	Uca sp.[2]	Fiddler crab	+	+
	Petrolisthes armatus	Porcelain crab	++++	+++
Mollusca Class Amphineura	*Chaetopleura apiculata*	Eastern chiton	+	+

Table B1. (Continued)

Phylum	Organism	Common Name	Occurrence[1]	
			Intake	Discharge
Class Gastropoda	*Diodora cayenensis*	Keyhole limpet	+	
	Crepidula plana	Eastern white slipper	++	+
	Crepidula aculeata	Spiny slipper	+	
	Haminoea sp.	Paper bubble	+	
	Urosalpinx tampaensis	Tampa drill	++	+
	Crassispira sanibelensis	Sanibel drill	+	
	Terebra sp.	Auger	+	+
Class Gastropoda	*Busycon sp.*[2]	Whelk	+	
	Unidentified Opisthobranch	Sea slug	+	
Class Bivalvia	*Crassostrea virginica*	American oyster	++++	++++
	Brachiodontus sp.	Ribbed mussel	+++	++
	Tellinia tampaensis	Tampa tellin	+	
	Arcopsis adamsi	Adam's ark	+	++
	Lithophaga bisulcata	Date mussel		+

Table B1. (Continued)

Phylum	Organism	Common Name	Occurrence[1]	
			Intake	Discharge
Echinodermata				
Class Ophiuroidea	(cf. *Ophioderma sp*.)	Brittle starfish	+	
Class Holothuroidea	(cf. *Cucumaria sp*.)	Sea cucumber	+	
Chordata				
Class Ascidiacea	(cf. *Molgula sp*.)	Sea squirt	+	+
	Unidentified Tunicate	Sea squirt	+	
Vertebrata				
Class Osteichthyes	*Opsanus beta*	Toad fish	+	

[1] Relative abundance indicated by number of crosses: + = rare; ++ = occasional; +++ = common; ++++ = abundant.

[2] Observed and noted but not taken in biomass samples.

Table B2. Seasonal trends of abundance, biomass and diversity for benthic animal communities inhabiting the intertidal zone of intake (I) and discharge (D) canal ecosystems at Crystal River power plant, Florida.[a]

Date		Abundance		Biomass		Species Richness			
						SPP/0.25 m^2		SPP/10^3 individs.[b]	
		I	D	I	D	I	D	I	D
		No/m^2		g dry/m^2					
1974									
Jun 30		556	684	8.4	16.0	21	12	29.4	16.1
Jul 17		---	1604	---	13.2	---	13	---	15.0
		---	1540	---	44.0	---	13	---	15.1
Jul 30		1652	---	36.0	---	19	---	21.8	---
		2560	---	19.6	---	15	---	16.0	---
Early	$\bar{x}$	1589	1276	21.3	24.4	18.3	12.7	22.4	15.4
Summer	±SE	±229	±299	±8.1	±9.8	±1.8	±.4	±3.9	±.4
Aug 13		4680	1992	40.8	38.4	17	13	16.6	14.5
		3336	1580	30.0	27.6	15	12	15.4	13.9
Sep 7		6008	1920	44.0	49.2	17	11	16.1	12.3
		3888	1640	27.2	32.8	18	12	18.1	13.8
1973									
Sep 13		4480	2148	56.4	116.4	18	11	17.7	12.1
Sep 17		---	1320	---	56.0	---	12	---	14.3
		---	2820	---	66.8	---	12	---	12.6
Late	$\bar{x}$	4478	1917	39.7	55.3	17.0	11.9	16.8	13.4
Summer	±SE	±449	±184	±5.3	±11.4	±0.6	±0.3	±0.5	±0.4

Table B2. (Continued)

Date		Abundance		Biomass		Species Richness			
		I	D	I	D	SPP/0.25 m^2		SPP/10^3 individs.[b]	
		No/m^2		g dry/m^2		I	D	I	D
1974									
Nov 30		3804	1720	44.4	42.8	17	13	17.1	14.8
Dec 1		4376	1100	37.6	24.4	19	14	18.8	17.2
Fall	$\bar{x}$	4090	1410	41.0	33.6	18	13.5	18.0	16.0
	±SE	±286	±310	±3.4	±9.2	±1	±.5	±.8	±1.2
1975									
Feb 13		2292	1348	22.8	30.4	14	17	15.2	20.2
Feb 14		8072	1788	32.4	37.4	18	14	16.3	15.9
		3712	1088	30.4	32.4	16	17	16.2	20.9
		---	1512	---	---	---	18	---	21.0
Winter	$\bar{x}$	4692	1434	28.5	33.3	16.0	16.5	15.9	19.3
	±SE	±1753	±148	±3.0	±2.1	±1.1	±0.9	±.4	±1.4
Mar 27		2304	904	12.4	13.6	23	17	25.0	21.7
		3308	796	27.2	12.4	26	17	26.8	22.2
		2700	1540	29.2	27.2	25	16	26.5	18.6
May 10		2348	396	27.6	22.8	18	12	19.5	18.0
		1280	672	27.6	14.0	16	12	19.2	15.6

Table B2. (Continued)

Date		Abundance		Biomass		Species Richness			
		I	D	I	D	SPP/0.25 m^2		SPP/10^3 individs.[b]	
		No/m^2		g dry/m^2		I	D	I	D
Spring	$\overline{x}$ ±SE	2388 ±330	862 ±190	24.8 ±3.1	18.0 ±3.0	21.6 ±2.0	14.8 ±1.0	23.4 ±1.7	19.2 ±1.2
Annual[c] Mean	$\overline{x}$ ±SE	3551 ±517	1326 ±160	31.2 ±3.5	31.2 ±4.7	18.3 ±1.2	14.3 ±0.9	19.2 ±1.6	17.2 ±1.2

[a] Samples were collected by hand from randomly selected quadrat in littoral and shallow subtidal zone (see Fig. 4 for station locations). Sediment and organisms were taken from within 0.25 m^2 frame to a depth of about 151 m below the semdiment surface and returned to lab for sorting, weighting and identification with 24 hrs.

[b] Number of species (S) which would be found in esamining 1000 individuals (N) was estimated assuming the following relationship S = K log N, where K is a characteristic diversity index.

[c] Average of four seasonal means, with summer season considered in halves.

Table B3. Seasonal trends of abundance and biomass for adult oysters and spat in benthic intertidal animal communities of the intake (I) and discharge (D) canal ecosystems.

Date	Abundance, No/m^2		Biomass, g/m^2		Spat, No/m2	
	I	D	I	D	I	D
1974						
June 30	0	48	0	9.6	44	0
Jul 17	--	116	--	(19.6)[a]	--	0
	--	160	--	25.2	--	0
Jul 30	136	--	6.4	--	456	--
	84	--	2.8	--	552	--
Early $\bar{x}$ Summer ±SE	73 ±40	108 ±32	3.1 ±2.0	18.1 ±4.6	352 ±157	0 0
Aug 13	36	32	4.4	1.2	2488	0
	68	172	8.8	(11.6)[a]	1524	16
Sep 7	92	68	9.6	7.6	1884	8
	84	28	8.8	1.2	2320	12
1973						
Sep 13	220	--	(26.0)[a]	--	696	--
Sep 14	--	200	--	(12.0)[a]	--	0
Sep 15	--	212	--	(26.0)[a]	--	0
Sep 17	--	284	--	8.4	--	0
Late $\bar{x}$ Summer ±SE	100 ±32	142 ±38	11.5 ±3.7	9.7 ±3.2	1782 ±319	5 ±3
1974						
Nov 30	--	44	--	8.0	--	112
	--	32	--	4.8	--	84

Table B3. (Continued)

Date	Abundance, No/m^2		Biomass, g/m^2		Spat, No/m^2	
	I	D	I	D	I	D
Dec 1	0	--	0	--	488	
	36	--	1.2	--	1412	
Fall $\bar{x}$ ±SE	18 ±18	38 ±6	0.6 ±.6	6.4 ±1.6	950 ±462	98 ±14
1975						
Feb 13	16	168	3.2	22.4	716	168
Feb 14	32	104	6.8	17.2	1984	124
	76	148	7.6	6.4	1404	16
	--	48	--	2.8	--	56
Winter $\bar{x}$ ±SE	41 ±18	117 ±27	5.9 ±1.4	12.2 ±4.6	1368 ±369	91 ±34
Mar 27	4	28	0	2.0	712	64
	0	40	0	4.0	1064	28
	0	60	0	8.0	1060	72
May 10	8	48	0.4	3.2	408	16
	0	40	0	4.0	204	24
Spring $\bar{x}$ ±SE	2.4 ±2	43 ±5	0.1 ±.1	4.2 ±1.0	690 ±172	41 ±12
Annual[b] $\bar{x}$ Mean ±SE	37 ±18	81 ±23	3.5 ±1.8	9.2 ±2.3	1019 ±141	58 ±23

[a] Biomaxx estimated from length-weight regression.

[b] Average of four seasonal means, with summer season considered in two halves.

Table B4. Seasonal trends of crab abundance and biomass for benthic intertidal communities of intake and discharge canal ecosystems.

Date	Mud Crabs[a]				Porcelain Crabs[a]			
	No./m^2		g dry/m^2		No./m^2		g dry/m^2	
	I	D	I	D	I	D	I	D
1974								
Jun 30	40	424[b]	0.4	5.2	92	--	0.8	--
Jul 17	--	452	--	12.8[c]	--	120	--	0.8
	--	596	--	14.8	--	112	--	1.2
Jul 30	28	--	2.0	--	452	--	3.2	--
	72	--	8.0	--	1296	--	8.0	--
Early Summer $\bar{x}$ ±SE	46.7 ±13.5	491 ±54	3.5 ±2.2	10.9 ±3.0	613 ±359	116 ±3	4.0 ±2	1.0 ±.1
Aug 13	96	780	22.8	22.8	764	12	10.4	0
	68	756	5.6	13.6	844	4	9.2	0
Sept 7	56	728	12.4[c]	13.2[c]	1748	4	20.0	0
	40	576	4.8	6.8	1292	0	11.6	0
1973								
Sep 13	--	536	--	29.6[b]	1604	--	26.4	--
Sep 17	--	316	--	5.6	--	--	--	0
	--	672	--	7.2	--	0	--	
Late Summer $\bar{x}$ ±SE	65 ±12	623 ±62	11.4 ±4	14.1 ±3	1250 ±228	4.0 ±2	15.5 ±4	0 ±0
1974								
Nov 30	120	584	9.2	8.8	2476	40	27.6	0.4
Dec 1	108	352	5.6	5.6	1876	32	25.6	0.4
Fall $\bar{x}$ ±SE	114 ±6	468 ±116	7.4 ±1.8	7.2 ±1.6	2176 ±301	36 ±4	26.6 ±1	0.4 ±0

Table B4. (Continued)

Date		Mud Crabs[a]				Porcelain Crabs[a]			
		No./m^2		g dry/m^2		No./m^2		g dry/m^2	
		I	D	I	D	I	D	I	D
1975									
Feb 13		64	52	13.6	2.4	212	32	2.8	0.4
Feb 14		120	44	8.0	5.6	1048	16	14.8	1.2
		128	32	6.4	13.6	1060	24	14.0	0.4
Winter	$\bar{x}$	104	42.7	9.3	7.2	773	24.0	10.5	0.7
	±SE	±21	±6	±2	±4	±283	±5	±4	±.3
Mar 27		64	12	1.6	6.4	260	12	4.0	0.8
		128	16	10.0	3.2	428	20	5.2	0.8
		80	32	7.2	11.2	264	24	3.2	1.6
May 10		92	44	8.8	13.2	504	28	8.0	4.0
		112	16	15.6	1.6	700	60	9.6	4.8
Spring	$\bar{x}$	95	24	8.6	7.1	431	28.8	6.0	2.4
	±SE	±12	±6	±2.3	±2.0	±82	±8	±1.2	±0.9
Annual Mean[d]	$\bar{x}$	92	273	8.2	8.5	1078	37.2	13.2	1.0
	±SE	±13	±140	±.5	±1.3	±381	±8	±4.6	±0.5

[a] Biomass of organic matter estimated as 0.3 x whole wt. (Day et al., 1973; Nixon et al., 1971).

[b] Biomass estimated from biomass-individual regressions.

[c] Average of four seasonal means, with summer season considered in halves.

Table B5. Seasonal trends of abundance and biomass for barnacles, mussels and serpulids in the benthic intertidal communities of the intake (I) and discharge (D) canal ecosystems.

Date	Barnacles[a]				Mussels[a]				Serpulids[b]	
	No./m^2		g dry/m^2		No./m^2		g dry/m^2		No./m^2	
	I	D	I	D	I	D	I	D	I	D
1974										
Jun 30	176	52	5.2	1.2	140	0	2.4	0	64	160
Jul 17	--	284	--	(2.4)[c]	--	12	--	∿0	--	520
	--	192	--	2.8	--	16	--	∿0	--	400
Jul 30	84	--	0.8	--	204	--	0.8	--	240	--
	60	--	0.4	--	108	--	0.4	--	320	--
Early Summer $\bar{x}$ ±SE	107 ±36	176 ±68	2.1 ±1.4	2.1 ±.5	151 ±28	9.3 ±5	1.2 ±.6	0 0	208 ±76	360 ±107
Aug 13	92	532	2.8	14.4	68	24	0.4	0	900	540
	80	100	3.6	2.4	180	8	2.8	0.2	420	480
Sep 7	16	596	0.4	28.0	340	8	2.4	0.4	1080	480
	16	500	0.2	24.0	208	20	1.2	0.8	280	400
1973										
Sep 13	0	880	0	60.4	512	0	2.0	0	800	--
Sep 17	--	668	--	38.0	--	0	--	0	--	--
	--	1088	--	51.2	--	0	--	0	--	760
Late Summer $\bar{x}$ ±SE	40.8 ±19	623 ±118	1.4 ±0.7	31.2 ±7.7	262 ±74	8.6 ±4	1.8 ±.4	0.2 ±.1	696 ±150	532 ±66

Table B5. (Continued)

Date	Barnacles^a				Mussels^a				Serpulids^b	
	No./m^2		g dry/m^2		No./m^2		g dry/m^2		No./m^2	
	I	D	I	D	I	D	I	D	I	D
1974										
Nov 30-	228	468	5.6	25.6	160	8	1.2	∿0	28	384
Dec 1	216	264	4.0	13.9	260	0	1.2	∿0	280	104
Fall $\bar{x}$	222	366	4.8	19.6	210	4	1.2	0	154	244
±SE	±6	±102	±.8	±4	±50	±4	±0		±126	±140
1975										
Feb 13-	116	696	2.8	5.2	84	28	0.6	0.4	920	172
Feb 14	4	1028	0.1	13.2	216	4	1.6	∿0	4428	260
	32	516	0.8	8.0	232	4	1.6	∿0	684	228
	--	1104	--	8.8	--	8	--	∿0	--	236
Winter $\bar{x}$	51	836	1.2	8.8	177	11	1.3	0.1	2011	224
±SE	±34	±139	±.9	±1.7	±48	±6	±.4	±.1	±1220	±19
Mar 27	68	360	2.8	3.6	176	24	1.2	∿0	680	284
	72	264	4.0	4.0	92	52	(0.8)^c	0.4	780	260
	124	564	4.8	5.2	172	32	(1.0)^c	∿0	400	240
May 10	4	88	0.1	0.6	16	8	(0.4)^c	∿0	1240	160
	4	144	0.1	3.2	24	16	(0.2)^c	∿0	160	320

Table B5. (Continued)

Date		Barnacles[a]				Mussels[a]				Serpulids[b]	
		No./m^2		g dry/m^2		No./m^2		g dry/m^2		No./m^2	
		I	D	I	D	I	D	I	D	I	D
Spring	$\bar{x}$	54	284	2.4	3.3	96	26	0.7	0.1	652	253
	±SE	±23	±85	±1	±.8	±35	±8	±.2	±.05	±183	±27
Annual Mean[d]	$\bar{x}$	100	471	2.5	12.1	172	13	1.2	0.1	817	292
	±SE	±41	±124	±.8	±3.7	±27	±5	±.2	±.03	±411	±52

[a] Biomass of organic matter estimated as 0.2 x weight of whole animal (Day et al., 1973; Nixon et al., 1971).

[b] Abundance recorded to nearest five individuals.

[c] Biomass estimated from biomass-individual regression.

[d] Annual means are average of four seasonal means, where summer season is considered in two halves.

APPENDIX C

Detailed data to describe the nekton community in power plant canal ecosystems at Crystal River.

Table C1. List of nekton species caught by gill net in canal ecosystems in March and June 1975.

Order	Species	Common Name	Occurrence	
			Intake	Discharge
Squaliformes	*Charcharhinus limbatus*	Blacktip shark	+	
Rajiformes	*Dasyatis sabina*	Atlantic stingray	+	+
	Dasyatis sayi	Bluntnose stingray	+	
Semionotiformes	*Lepisosteus oculatus*	Spotted gar	+	+
Elopiformes	*Elops saurus*	Ladyfish	+	+
Clupeiformes	*Harengula pensicolae**	Scaled sardine	+	
	Opisthonema oglinum	Atlantic thread herring	+	
	*Anchoa mitchilli**	Bay anchovy	+	
Siluriformes	*Arius felis*	Sea catfish	+	
	Bagre marinus	Cafftopsail catfish	+	+
Batrachoidiformes	*Opsanus beta*	Gulf toadfish	+	
Lophiiformes	*Oegocephalus radiatus**	Polkadot batfish	+	
Atheriniformes	*Strongylura marina**	Atlantic needlefish	+	
	*Menidia beryllina**	Tidewater silversides	+	

Table C1. (Continued)

Order	Species	Common Name	Occurrence	
			Intake	Discharge
Perciformes	*Centropristis melana*	Southern sea bass	+	
	Pomotomus saltatrix	Bluefish	+	
	Caranx hippos	Crevalle jack	+	+
	Chloroscombrus chysurus	Atlantic bumper	+	
	*Oligoplites saurus**	Leatherjacket	+	
	Haemulon plumieri	Grunt	+	
	Archosargus probatocephalus	Sheepshead	+	+
	Diplodus holbrooki	Spottail pinfish	+	
	Cynoscion nebulosus	Spotted sea trout	+	
	Pogonias cromis	Black drum	+	+
	Chaetodipterus faber	Spadefish	+	+
	Mugil cephalus	Striped mullet	+	+
	Scomberomorus maculatus	Spanish mackerel	+	

Table Cl. (Continued)

Order	Species	Common Name	Occurrence	
			Intake	Discharge
Pleuronectiformes	*Paralichthys albigutta*	Gulf flounder	+	
Tetraodontiformes	*Lactophyrus triqueter*	Scrawled cowfish	+	

---

[a] These smaller fish were caught by tangling rather than gilling and their capture may be considered fortuitous and non-quantitative.

Table C2. Mark-recapture data for estimating population density of polkadot batfish, *Ogcocephalus radiatus*, in intake canal at Crystal River power plant.[a]

Date 1973	Zone[b]	Spoil Bank	Number of Fish	Number Returns
Sept. 19	4	North	54	0
		South	22	0
Sept. 20	2	North	7	0
		South	2	0
	1	North	24	0
		South	2	0
Sept. 26	1	North	20	1
Sept. 27	4	North	16	2
		South	30	0
		North	47	0
		North	49	3
Sept. 28	3	North	28	0
		North	42	2
		North	29	0
		South	5	0
		South	9	0
Sept. 29	2	North	32	0
		South	5	0
Totals		North South	348 77	8 0

[a] Data were taken from unpublished measurements of D. Dorman and B. Sutton (1973), by permission. Fish were sampled by SCUBA.

[b] Canal is divided into 4 zones, about 1.25 km long and numbered 1-4 starting at the power plant.

Table C3. SCUBA census data for estimating population density of the polkadot batfish, Ogcocephalus radiatus, in intake canal at Crystal River power plant.[a]

Date 1973	Transect No.[b]	Substrate	Depth, m	Fish per transect	Population Density
Oct. 3	1	sand/silt	7.5	1	$\frac{22\ \text{fish}}{600\ \text{m}^2} = 0.037/\text{m}^2$
	2	sand	7.0	1	
		grass/mud	2.5	0	
	3	sand	4.5	3	
		silt/algae	2.0	2	
	4	sand/rock	7.0	10	
	5	sand/rock	7.5	5	
	6	mud/grass	2.0	0	
Oct. 4	7	sand/algae	2.0	0	$\frac{1\ \text{fish}}{13{,}000\ \text{m}^2} = 8 \times 10^{-5}/\text{m}^2$
	8	sand/shell	2.0	1	
	9	sand/shell	2.0	0	
	10	sand/algae	2.0	0	
	11	sand/shell	2.0	0	
	12	sand/shell	2.0	0	
	13	sand/shell	2.0	0	
Oct. 10	14	sand/algae	2.0	0	
	15	sand/shell	2.0	0	
	16	sand/shell	2.0	0	
	17	sand/algae	2.0	0	
	18	sand/shell	2.0	0	
	19	sand/shell	2.0	0	
Oct. 11	20	sand/rock	6.5	3	$\frac{17\ \text{fish}}{500\ \text{m}^2} = 0.034/\text{m}^2$
	21	rock/snad	6.5	2	
	22	sand/gravel	7.0	8	
	23	gravel/rock	6.5	2	
	24	sand/rock	6.5	2	

[a] Data were taken from unpublished measurements of D. Dorman and B. Sutton, by permission. Fish were observed by SCUBA and counted along 50 m transects, 2 m wide. Transects were laid out with nylon rope at various angles relative to the canal spoil banks.

[b] Transects 1-6 were within the bilaterally confined canal. Transects 7-17 were done in open bays. Transects 20-24 were done in the outer part of canal, where there is no south spoil bank.

Table C4. Measurements of nekton populations in power plant canal ecosystems at Crystal River.

Date 1975	Location (Position[a] on net)	Species	Total Catch Number	lbs.[b]
Mar 19	Intake canal (enclosed)	*Caranx hippos*	28	55.5
		Bagre marinus	3	6.0
		Cynoscion nebulosus	2	5.7
		Chaetodipterus faber	6	2.8
		Diplodus holbrooki	3	2.5
		Dasyatis sabina	1	0.5
		Anchoa mitchilli	1	0.3
		Crabs, Shrimp, etc.	6	1.3
	Total		50	74.6
Mar 19	Intake canal (headed in)	*Caranx hippos*	14	30.5
		Bagre marinus	1	1.4
		Chaetodipterus faber	4	1.9
		Centropristis melana	1	1.3
		Strongylura marina	1	.2
		Crabs, Shrimp, etc.	4	1.7
	Total		25	37.0
Mar 19	Intake canal (headed out)	*Caranx hippos*	9	19.6
		Bagre marinus	4	2.0
	Total		13	21.6

Table C4. (Continued)

Date 1975	Location (Position[a] on net)	Species	Total Catch Number	Total Catch lbs.[b]
June 25	Intake canal (enclosed)	*Caranx hippos*	8	12.5
		Carcharhinus limbatus	4	16.2
		Chloroscombrus chrysurus	16	4.2
		Elops saurus	3	2.8
		Bagre marinus	1	2.1
		Paralichthys albigulta	1	1.5
		Other fish	8	3.6
		Crabs, Shrimp, etc.	6	1.6
	Total		47	44.5
June 25	Intake canal (headed in)	*Lepisosteus oculatus*	4	36.3
		Carcharhinus limbatus	1	8.2
		Cynoscion nebulosus	2	3.2
		Bagre marinus	4	10.0
		Opisthonema oglinum	12	3.2
		Chloroscombus chrysurus	6	1.2
		Scomberomorus maculatus	3	1.5
		Pogonias cromis	1	2.1
		Harengula pensicolae	9	1.0
		Elops saurus	1	0.5
		Other fish	18	3.9
		Crabs, etc.	3	1.8
	Total		64	72.9

Table C4. (Continued)

Date 1975	Location (Position on net)	Species	Total Catch Number	Total Catch lbs.
June 25	Intake canal (headed out)	*Dasyatis spp.*	2	25.8
		Bagre marinus	9	10.2
		Lepisosteus oculatus	1	7.0
		Carcharhinus limbatus	1	2.7
		Pogonias cromis	1	3.2
		Harengula pensicolae	23	3.4
		Mugil cephalus	1	1.8
		Cynoscion nebulosus	1	1.3
		Scomberomorus maculatus	2	0.8
		Other fish	15	1.7
	Total		56	57.9
Mar 20	Discharge canal (enclosed)	*Bagre marinus*	102	183.5
		Caranx hippos	2	5.5
		Chaetodipterus faber	9	3.4
		Crabs, etc.	4	2.0
	Total		117	194.4
Mar 20	Discharge canal (in canal headed in)	*Bagre marinus*	7	8.6
		Chaetodipterus faber	2	1.0
	Total		9	9.6
Mar 20	Discharge canal (in canal headed out)	*Bagre marinus*	5	11.6
		Chaetodipterus faber	1	0.7
	Total		6	12.3

Table C4. (Continued)

Date 1975	Location (Position on net)	Species	Total Catch	
			Number	lbs.
Mar 20	Discharge canal (at end of canal, headed in)	*Bagre marinus*	29	59.8
		Caranx hippos	165	355.2
		Lepisosteus oculatus	1	10.5
		Chaetodipterus faber	3	2.8
	Total		198	428.3
Mar 20	Discharge canal (at end of canal, headed out)	*Bagre marinus*	17	34.8
		Caranx hippos	80	236.3
		Lepisosteus oculatus	2	29.0
		Chaetodipterus faber	4	5.7
		Mugil cephalus	3	5.7
		Crabs, etc.	3	1.2
	Total		109	312.7
June 26	Discharge canal (enclosed)	*Pogonias cromis*	2	1.8
		Archosargus probatocephalus	1	0.6
		Elops saurus	1	0.6
		Crabs, etc.	16	5.6
	Total		20	8.6

[a] See Methods for description of net placement. "Enclosed" means corralled between 2 nets; "headed in or out" means caught on outside of corral nets moving out of canal or further in; other single-line of nets across end of canal captured fish moving in and out of canals.

[b] Fresh weights measured in field.

Table C5. Analyses of stomach contents of selected fish caught in gill nets in canals at Crystal River power plant.

Species	Stnd. Length, mm	Food Items	
		Description	Quantity
March, 1975 (Intake Canal):			
Caranx hippos	295	Unident. fish parts	0.5 g (wet)
Jack crevalle	290	Unident. fish parts	3.3 g (wet)
	290	Unident. fish parts	2.5 g (wet)
	290	Unident. fish parts	3.6 g (wet)
	285	Empty	
	285	Silverside	0.5 g (wet)
		Shrimp	0.2 g (wet)
		Unident. fish parts	0.4 g (wet)
	280	Unident. fish parts	3.7 g (wet)
	275	2 Silversides 50 mm 40 mm	2.0 g (wet)
		Unident. fish parts	0.7 g (wet)
Bagre marinus	390	Unident. fish parts	1.5 g (wet)
Gafftopsail catfish			
Pomatomus saltatrix	205	Unident. fish parts	6.0 g (wet)
Bluefish			
Haemulon plumieri	120	Polychaetes & Mysids	1.0 g (wet)
White grunt	120	Shrimp 8 Porcelain crabs	1.5 g (wet)
Orthopristis chrysoptera	140	Crab parts	0.5 g (wet)
Pigfish			
Paralichthys albigutta	120	Empty	
Gulf flounder			

Table C5. (Continued)

Species	Stnd. Length, mm	Food Items		
		Description		Quantity
March, 1975 (Discharge Canal):				
Archosargus probatocephalus	250	Crab parts		---
Sheepshead				
Pogonias cromis	300	Crab parts		---
Black drum	250	Empty		---
June, 1975 (Intake Canal):				
Carcharhinus limbatus	630	2 Blenny	85 mm	10 g (wet)
			70 mm	
Blacktip shark			140 mm	
	480	Seatrout	100 mm	8 g (wet)*
		Black drum	150 mm	
		Snapper	---	
		Unident. fish parts		
	480	Ladyfish	220 mm	4 g (wet)*
		Crab parts	---	
	470	Clupeid	130 mm	3 g (wet)*
Dasyatis sabina	230	Shrimp		2 g (wet)*
Atlantic stingray				
Dasyatis sayi	540	Mud shrimp		4 g (wet)*
		Oyster shells		
Bluntnose stingray				
Bagre marinus	340	Mud crab		7 g (wet)
		Porcelain crab		
Gafftopsail catfish		Unident. fish parts		
		Sea grass		8 g (wet)

Table C5. (Continued)

Species	Stnd. Length, mm	Food Items: Description	Food Items: Quantity
Bagre marinus	400	*Anguilla sp.* 390 mm	
Gafftopsail catfish	400	Mud shrimp Mud crabs	8.5 g (wet)
	380	Toadfish 10 mm	15 g (wet)
		Unident. fish parts Porcelain crabs	11 g (wet)
		Seagrass	3 g (wet)
	310	*Panopeus herbsti*	18 g (wet)
Caranx hippos	330	Silverside 25 mm	1 g (wet)*
Jack crevalle	300	Empty	
	295	Silverside parts	2 g (wet)*
	280	Silversides	25@ 25 mm 3@ 25-40 mm 10 mm 5 g (wet)*
	280	Empty	
	275	7 Silversides 25-45 mm	2 g (wet)*
Elops saurus	325	Unident. fish parts	3 g (wet)*
Ladyfish			
Cynoscion nebulosus	410	Toadfish or Goby 100 mm	5 g (wet)*
Speckled seatrout	300	Atlantic bumper Unident. fish parts Isopod (*Lygia*)	4 g (wet)
Pogonias cromis	330	Mud crabs Mud shrimp *Nassa* snails Nemeteans	8 g (wet)*
Black drum			
Mugil cephalus	345	Plant detritus Unident. detritus Diatoms Sponge	---
Striped mullet			

Table C5. (Continued)

Species	Stnd. Length, mm	Food Items	
		Description	Quantity
June, 1975 (Discharge Canal):			
Pogonias cromis Black drum	310	1000 (+) juvenile *Nassa* Mud shrimp 20 Porcelain crabs 10 Mud crabs	10 g (wet)*

* Weights of these stomach contents were estimated by length-weight relationships (Homer, personal comm.).

APPENDIX D

Derivation of formula for estimating blue crab populations at Crystal River, taking migration into account.

An equation is developed in this appendix to estimate blue crab populations under conditions of active migration to and from the study area. The underlying assumptions for any mark-recapture estimate of populations are given in the Methods section, and these are also appropriate to this formulation, except that migration is allowed to occur in the present case. Previous workers have derived general expressions for estimating populations from multiple mark-recapture data with emigration (death) and/or immigration (dilution) (Darroch, 1959; Jolly, 1963; Jolly, 1965). However, each of these methods pertained to multiple sets of data for populations in a single, defined area. In the situation at Crystal River, captured crabs were tagged according to place and time of catch, and two distinct, adjacent areas were sampled. This allowed explicit estimates of migration between sampling regions. In addition, numbers of recaptures were limited so that Schnabel-type multiple estimates were not possible.

The major processes and components of concern are illustrated in Fig. D1. If these assumptions (above) are met, the ratio of total population to marked population can be estimated as,

$$\frac{\hat{N}_c}{\bar{m}_c} = \frac{C_c}{r_c} \qquad \text{(D1)}$$

But the actual number of marked crabs in the canal is not equal to the number of crabs caught in the canal, marked and returned to the canal, because marked crabs move in and out of the canal. Therefore,

Figure D1. Energy diagram of major system components and processes for estimating blue crab populations in the intake canal at Crystal River power plant, taking crab migration into account. Abbreviations are

N_c = size of canal population

$\hat{N}_c$ = estimate of N_c

N_b = size of bay population

m_c = number of crabs caught, marked and returned to canal

$\bar{m}_c$ = actual number of marked crabs in N_c

m_b = number of marked crabs in N_b

C_c = number of crabs captured from N_c

C_b = number of crabs captured from N_b

r_c = number of marked crabs recaptured in canal

r_b = number of marked crabs recaptured in bays

r_{cn} = number crabs marked in bay, recaptured in canal

r_{bn} = number crabs marked in canal, recaptured in bay

n_c = number of crabs which were marked in bay and later moved into N_c

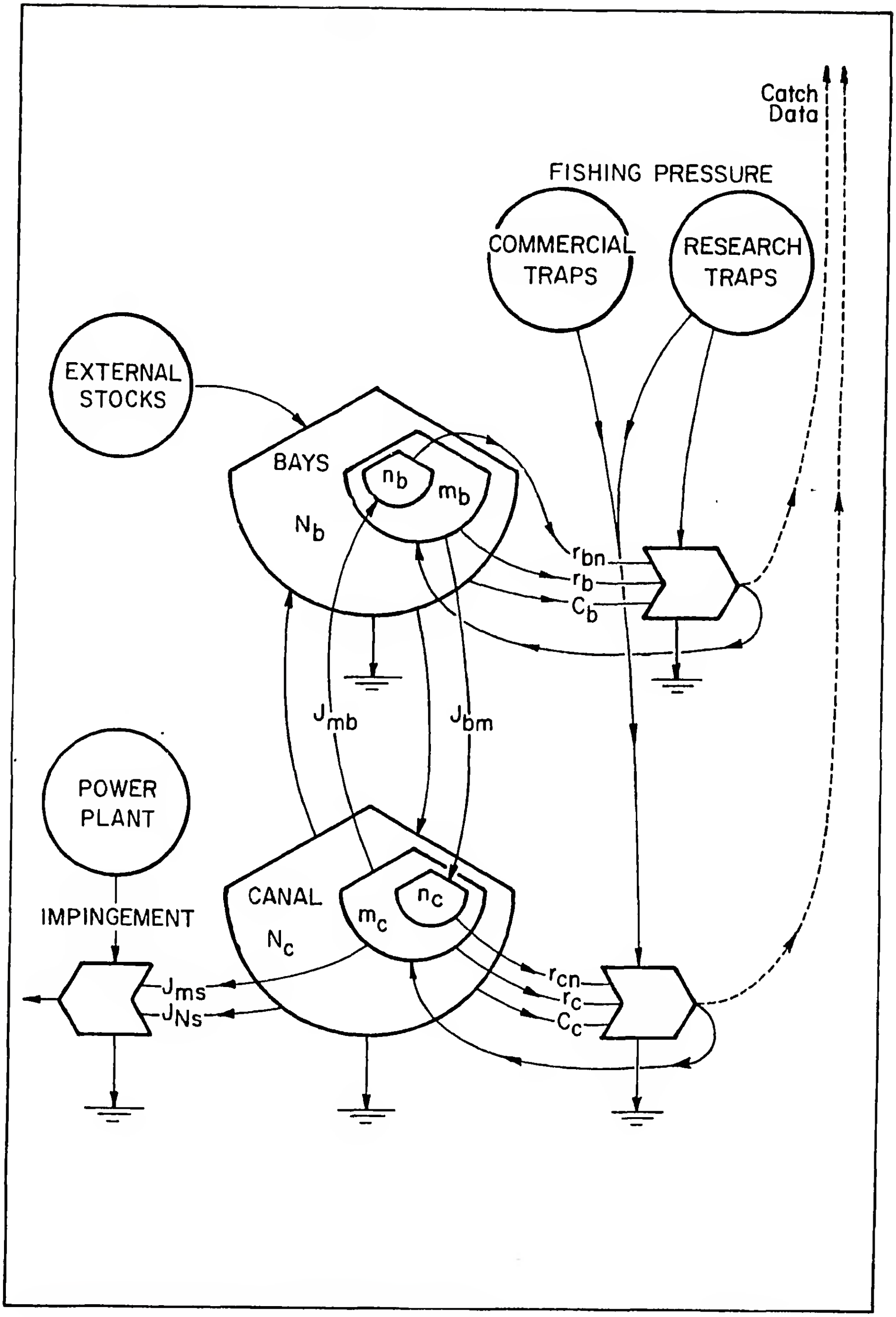
n_b = number of crabs which were marked in canal and later moved into N_b

J_{bm} = number of crabs marked in bays migrated to canals

J_{mb} = number of crabs marked in canal migrated to bays

J_{ms} = number marked crabs impinged on screens

J_{Ns} = total number crabs impinged


Catch
Data
FISHING PRESSURE
COMMERCIAL TRAPS
RESEARCH TRAPS
EXTERNAL STOCKS
BAYS
n_b
m_b
N_b
r_{bn}
r_b
C_b
J_{mb}
J_{bm}
POWER PLANT
IMPINGEMENT
CANAL
N_c
m_c
n_c
r_{cn}
r_c
C_c
J_{ms}
J_{Ns}

$$\overline{m}_c = m_c + J_{bm} - J_{mb} - J_{ms} \quad . \tag{D2}$$

Crabs migrate in the unmarked population, too; however it is reasonable to assume that for the entire canal population steady-state prevails and immigration is balanced by emigration plus death. At the end of a given time period, the number of marked crabs in the canal which were originally caught and marked in the bays (n_c) is equal to inputs minus outputs, so that

$$n_c = J_{bm} - r_{cn} \tag{D3}$$

and similarly the number of marked crabs in the bay which were originally caught and marked in the canals (N_b) is,

$$n_b = J_{mb} - r_{bn} \quad . \tag{D4}$$

In a manner analogous to the ratio equivalence of expression (D1), it can be assumed that recapture rates are proportional to stocks,*

$$\frac{n_c}{m_c} = \frac{r_{cn}}{r_c} \tag{D5}$$

and

$$\frac{n_b}{m_b} = \frac{r_{bn}}{r_b} \quad . \tag{D6}$$

Therefore, substituting equations (D5) and (D6) for n_c and n_b, respectively, into equations (D3) and (D4), and solving for J_{bm} and J_{mb}, we find that the migrations of marked crabs between bay and canal are as follows:

---

* To be most correct m_c and m_b in equations (D5) and (D6) should be $\overline{m}_c$ and $\overline{m}_b$; however, this approximation introduces only a small error to the overall calculation of $\hat{N}_c$ as long as the ratios of $\overline{m}_c/m_c$ and $\overline{m}_b/m_b$ are approximately between 0.5 and 2.0.

$$J_{bm} = r_{cn}(m_c/r_c + 1) \tag{D7}$$

$$J_{mb} = r_{bn}(m_b/r_b + 1) \quad . \tag{D8}$$

Substituting equations (D7) and (D8) into equation (D2), the number of marked crabs in the canal becomes,

$$\overline{m}_c = m_c + r_{cn}(m_c/r_c + 1) - r_{bn}(m_b/r_b + 1) - J_{ms} \quad . \tag{D9}$$

Finally, if we substitute equation (D9) into equation (D1) and solve for $\hat{N}_c$, we obtain the needed formula to estimate the canal blue crab population,

$$\hat{N}_c = \frac{C_c}{r_c}\left(m_c + r_{cn}\left(\frac{m_c}{r_c} + 1\right) - r_{bn}\left(\frac{m_b}{r_b} + 1\right) - J_{ms}\right) \quad . \tag{D10}$$

All terms in this expression can be estimated from the tagging data of Oesterling (1973, 1976).

APPENDIX E

Derivation of model equation to account for temperature effects on productivity.

A simplified relationship is developed in this appendix to describe the effects of temperature on photosynthesis. A complex exponential relationship between biological reaction rates and temperature was developed by Johnson, Eyring and Polissar (1954) and later refined in Eyring and Eyring (1963) and Johnson, Eyring and Stover (1974). This equation was derived from theoretical considerations of biochemical kinetics originating from the early work of Arrhenius.

$$I = \frac{aT \cdot \exp(-b/RT)}{1 + \exp((-C + kT)/RT)} \tag{E1}$$

where I = reaction rate, a = constant coefficient, b = a coefficient containing measures of the heat and pressure of activation, C = coefficient describing heat and pressure of protein deactivation, k = coefficient indicating entropy of deactivation, R = universal gas constant, and T = absolute temperature.

The fundamental concept underlying this relationship is that the net rate of a particular process under given conditions is a function of three reactions involving a single enzyme. They are (1) the catalytic reaction itself with enzymatic activation energy; (2) the reversible thermal inactivation of the enzyme, with a high heat and entropy of reaction as characteristic of proteins; (3) the process of enzyme destruction, also with high heats and entropies of (de-) activation. There is, thus, an equilibrium between native, active and denatured-inactive forms of the catalyst. "Denaturation" is often used only in reference to changes in solubility (usually considered irreversible), resulting from heat of other agents. However, Johnson, Eyring and Stover (1974) define "denaturation" in a more general sense as any reaction through which one or more properties (such as catalytic activity of enzymes, absorption spectrum or crystallizability), which are characteristic of the native protein, are reversibly or irreversibly lost.

Odum (1974) reinterpreted the temperature/reaction rate equation given in Eyring and Eyring (1963) to the following form,

$$J = \frac{N + \exp(-E/RT)}{1 + \exp(-\Delta F/RT)} \qquad \text{(E2)}$$

where J = reaction rate, N = constant, E = activation energy of reaction, ΔF = free energy difference in structural protein and its denatured state, and R and T are as in Eq. (E1). He showed that this equation yielded gradually increasing rates with temperature up to an optimum temperature beyond which reaction rate declined precipitously. The primary difference between Eqs. (E1) and (E2) is that T is multiplied times the exponential term in the numerator of Eq. (E1). Odum (1974) also described another temperature kinetic relationship suggested by Morowitz (1968), which similarly yielded an optimum-temperature form.

The simplified form of this temperature-reaction relationship used in this dissertation was derived beginning from Eq. (E2) after dropping N, since it did not appear in the original form of Eq. (E1). Thus, we have

$$J = \frac{\exp(-E/RT)}{1 + \exp(-\Delta F/FT)} \qquad \text{(E3)}$$

assuming a linear, Q_{10}-type approximation of the exponential terms for the limited temperature range encountered in this study, (Schmidt-Nielsen, 1975), then

$$k_X T \approx \exp(-X/RT) \quad . \tag{E4}$$

Therefore, we modify Eq. (E3) so that,

$$J = \frac{k_E T}{1 + k_{\Delta F} T} \quad . \tag{E5}$$

This can further be simplified using the first term of the "Geometric series" approximation for Eq. (E5),

$$J = k_E T(1 - k_{\Delta F} T) \quad . \tag{E6}$$

In a recent paper Watt (1975) has criticized some ecosystem modellers for using non-theoretically-derived equations to simulate temperature effects (e.g., R.A. Parker, 1974). He showed that the equations used by O'Neill et al. (1972) produced symmetrical near-parabolic temperature response around an optimum temperature. He cites examples in Watt (1968) where measured data indicated asymmetric response with sharp declines in rate for temperatures exceeding the optimum (as previously indicated characteristic of Eqs. (E1) and (E2)).

APPENDIX F

Detailed information for computer model of estuarine ecosystem.

Table F1. Differential equations describing model of estuary receiving waste discharges from Crystal River power plant.

PRIMARY PRODUCERS, P:

$$\dot{P} = \overset{\text{productivity}}{k_1(I)(1 - k_DS)(T(1 - k_T(T - 10)))\frac{N\cdot P}{(1 + k_PN\cdot P)}} + \overset{\text{phytoplankton import}}{J_8}$$

$$\overset{\text{export}}{- k_3P} \overset{\text{nekton herbivory}}{- k_4P\cdot N} \overset{\text{benthic herbivory}}{- k_5P(k_BB + F)} \overset{\text{death}}{- k_6P} \overset{\text{respiration}}{- k_7P}$$

NITROGEN, N:

$$\dot{N} = \overset{\text{nutrient uptake by plants}}{- k_2k_1(I)(1 = k_DS)(T(1 - k_T(T - 10)))\frac{N\cdot P}{1 + k_PN\cdot P}} + \overset{\text{import}}{J_9}$$

$$\overset{\text{recycling}}{+ k_{11}(k_{19}D + k_{16}B^2)} \overset{\text{export}}{- k_{10}N}$$

DETRITUS, D:

$$\dot{D} = \overset{\text{import}}{J_{20}} + \overset{\text{plant death}}{k_6P} \overset{\text{export}}{- k_{21}D} \overset{\text{benthic detritivory}}{- k_{17}D\cdot(k_BB + F)} \overset{\text{respiration}}{- k_{19}D}$$

$$\overset{\text{benthic death}}{+ k_{22}B} + \overset{\text{nekton death}}{k_{23}F} \overset{\text{nekton detritivory}}{- k_{31}D\cdot F}$$

BENTHIC INVERTEBRATES, B:

$$\dot{B} = \overset{\text{herbivory}}{k_5P(k_BB + F)} + \overset{\text{detrivitory}}{k_{17}D(k_BB + F)} \overset{\text{nekton predation}}{- k_{15}B\cdot F} \overset{\text{death}}{- k_{22}B} \overset{\text{respiration}}{- k_{16}\cdot B^2}$$

Table F1. (Continued)

NEKTON, F:

$$\dot{F} = \overset{\text{herbivory}}{k_4 P \cdot F} + \overset{\text{detritivory}}{k_{31} D \cdot F} + \overset{\text{predation}}{k_{15} B \cdot F} - \overset{\text{respiration}}{k_{14} F^3}$$

$$\overset{\text{death}}{- k_{23} F} + J_{13} + J_{12}$$

where,

$$J_{13} = .03, \quad \text{when} \quad \text{Temp} > 20^\circ\text{C}$$

$$= 0, \quad \text{when} \quad \text{Temp} \leq 20^\circ\text{C}$$

$$J_{12} = k_{24} F, \quad \text{when} \quad \text{Temp} \leq 20^\circ\text{C}$$

$$= 0, \quad \text{when} \quad \text{Temp} > 20^\circ\text{C}$$

TURBIDITY, S:

$$\dot{S} = J_S - k_S S$$

Table F2. Data sources for flows and storages used in model of estuary receiving waste discharges from Crystal River power plant.

Storage	Description	Calculation	Reference
N, NTR	Inorganic Nitrogen concentration	Assumes depth = 1 m; includes NH_3, NO_2 and NO_3	Gibson (1975)
P, PRD	Standing Stocks of Primary Producers	Benthic macrophytes plus phytoplankton	Van Tine (1974) Gibson (1975)
D, DET	Stocks of Biologically Active Detritus	Assume that detritus in water column plus aerated zone of sediment detritus are biologically active. aerated zone = 1 mm fraction organics = 0.04 seston concentration, 3.5-8.0 g/m^2 $(DET)_{sed} = (1\ g/cm^3)(.10\ dry/wet)(10^6\ cm^3/m^3) \times (.04\ org)(10^{-3}\ m) = 4\ g/m^2$	Kanwisher (1962) Cottrell (1974) Gibson (1975)
B, BEN	Standing Stocks of Benthic Invertebrates	Assuming oyster reefs occupy 7% of bay area and that dry wt/whole wt conversion is 10%, total benthic standing stocks are taken to include benthic macrofauna plus prorated oyster reef fauna. For control area reef animals: summer: 3.9 g/m^2 winter: 2.7 g/m^2 other macrofauna: summer: 11.0 g/m^2 winter: 3.8 g/m^2	Evink and Green (1974) Lehman (1975)
F, NEK	Standing Stocks of Nekton (Fish)	Assume drop-net data represents a consistent proportion of the total stocks. Assume 45% catch efficiency of drop nets for shallow bays. Range is (.9-4.7 g/m^2).	Adams (1974) Kjelson et al. (1973) Wagner (1973)

Table F2. (Continued)

Storage	Description	Calculation	Reference
S, TRB	Turbidity	Relative units ranging from 3-8. From Secchi disc and subphotometer data, extinction coefficients converted to relative units to fit model equation.	This study

Flow	Description	Calculation	Reference
J_9	Nitrogen Import	Assumes bay flushes once per day and mean depth - 1 m.	Gibson (1975)
J_8	Phytoplankton Import	Same as above	Gibson (1975)
T	Temperature	Monthly mean values at power plant	Smith (1976)
I	Insolation	Monthly mean values at Tampa	Smith (1976)
J_{20}	Seston Import	Relative units calculated for Secchi disc and subphotometer data	This study
J_6	Plant Death	Estimated by difference, assuming steady-state, $J_6 = J_1 + J_8 - J_3 - J_4 - J_5 - J_7$ $= 9.5 + .5 - .5 - .2 - .8 - 6.8$ $= 1.7$ g/m^2-day	
J_{19}	Detritus Respiration	Assume ∿ 20% of total resp. and assume production/respiration - .85 J_{19} - .2 (9.5/.85) = 2.2 g/m^2-day	Hargrave (1969) Smith (1976)
J_{17}	Benthic Detritivory	Assume ∿ 50% of benthic$_2$consumption J_{17} = .5 (1.7) = .9 g/m -day	Smith (1971)

Table F2. (Continued)

Flow	Description	Calculation	Reference
J_{16}	Benthic Respiration	Assume metabolic turnover rate of 5%/day $J_{16} = (13\ g/m^2)(.05/day)$ $= .65\ g/m^2\text{-day}$	Day et al. (1973)
J_{15}	Nektonic Predation on Benthics	Assume ∿ 50% of fishes' diets comprised of benthic invertebrates $J_{15} = .27$	Homer (1976) This study
J_{22}	Benthic Death Rate	Estimate by difference, assuming steady-state, $J_{22} = J_5 + J_{17} - J_{16} - J_{15}$ $= .8 + .9 - .65 - .27 = .78$	
J_1	Gross Primary Productivity	Free-water diurnal oxygen changes summer: 9.5 winter: 3.5 g/m^2-day	Smith (1976)
J_2	Nitrogen Uptake by Plants	Assume C:N = 106:16 and dry matter: carbon = 2 summer: .071 winter: .036	Odum (1971)
J_{10}	Nitrogen Export	Assume bay flushes once/day $J_{10} = .12\ g\ N/m^2\text{-day}$	Carder et al. (1973)
J_{11}	Nitrogen Recycling	Estimate by difference $J_9 + J_{11} = J_2 + J_{10}$ $J_{11} = .071 + .171 - .021\ g\ N/m^2\text{-day}$	
J_3	Phytoplankton Export	Assume bay flushes once/day $J_3 = 0.5$ (summer)	Carder et al. (1973)

Table F2. (Continued)

Flow	Description	Calculation	Reference
J_7	Plant Respiration	Assume $\sim$ 70% of gross production J_7 - .7 (9.5 g/m^2-day) = 6.8 g/m^2-day	Day et al. (1973)
J_5	Benthic Herbivory	Assume $\sim$ 50% of benthic comsumption is herbivorous. Therefore, J_5 = .5 (1.7) = .8 g/m^2-day	Smith (1971)
J_4	Nektonic Herbivory	Assume $\sim$ 25% of benthic consumption is detritivorous. Thus, J_4 = .25 (.6) = .15 g/m^2-day	Odum and Heald (1972)
J_{31}	Nektonic Detritivory	Assume fish diet to be 15-20% detritus J_{31} = .175 (.54) = .1 g/m^2-day	Odum and Heald (1972) Homer (1976)
J_{14}	Nektonic Respiration	Assume metabolic turnover rate of 3.3% J_{14} = 4.2 (0.33) = .15 g/m^2-day	Day et al. (1973) Pandian (1967)
J_{23}	Nektonic Death Rate	Estimate by difference, assuming steady-state conditions $J_{23} = J_4 + J_{15} + J_{31} - J_{14}$ $= .54 - .35 = .19$	
J_{21}	Detritus Export	Estimated by difference, assuming steady-state conditions $J_{21} = J_{20} + J_6 + J_{22} + J_{23} - J_{17} - J_{19}$ $= 6.5 + 1.7 + .8 + .2 - 2.2$ $= 7.0$	

Table F3. Calculations and assumptions for pathway rate coefficients used in model of estuary receiving waste discharges from Crystal River power plant.

Coefficient	Calculation
k_D Shading Rate	In July Secchi disc = 0.9 m which is equivalent to $k = 1.15/m$. Therefore, $\exp(-k) = .32$. Letting silt, $S = 8.0$ relative units. $(1 - 8\ k_D) = .32$ $k_D = .083$
k_T Temperature Inhibition	Assuming that when T = 45°C, productivity is essentially equal to zero (Eppley, 1973). $(1 - k_T(T - 10)) = 0$ $k_T = 1/35 = .0286$
k_B Benthic Feedback	Assume that in summer fish and benthic populations have equal influence in stimulating benthic consumption via mutualistic factors. $k_B B = F$ $k_B = F/B = 4.1/12.3 = .33$
k_p Half Saturation	"Half-saturation constant" (k_S) for coastal waters = 8 μ M/1 (Eppley et al., 1972) for nitrate. $k_S + N)$ -- $(1 + k_p P \cdot N) = ((1/k_p \cdot P) + N$ $k_S = 8\ \mu\ M/1 = .112$ g NO_3-N/m^2 (assuming depth - 1 m) = .33 g N/m^2 (assuming NO_3 33% of total N) $k_P = (1/k_S \cdot P) = 1/.33(60)) = .05$
k_1 Primary Productivity	$J_1 = 1 = k_1(5.5)(1 - (.083)\ 2.8)\ 20.5(1 - (.0286)\ 10.5)$ $\times\ 60\ (.62)/(1 + .05)\ (60)\ .62)$ $k_1 = .02$
k_2 Nitrogen Uptake	Assume C:N = 106:16 and dry matter: carbon = 2 (Odum, 1972). $J_2 = 0.68 = k_2(9)$ $k_2 = .075$
k_3 Phytoplankton Export	$J_3 = k_3 P$ Summer: $k_3 = 0.5/62 = .008$ Winter: $k_3 = 0.36/42 = .009$
k_4 Nekton Herbivory	$J_4 = k_4 PF$ Summer: $k_4 = .17/(62)(4.1) = .00067$ Winter: $k_4 = .03/(42)(1.1) = .00067$
k_5 Benthic Herbivory	$J_5 = k_5 P(k_B B + F)$ Summer: $k_5 = .8/62(.33(13.5) + 4.1) = .0015$ Winter: $k_5 = .6/42(.33(10.4) + 1.1) = .0026$

Table F3. (Continued)

Coefficient	Calculation
k_6 Plant Death	$J_6 = k_6P$ Summer: $k_6 = 1.5/62 = .02$ Winter: $k_6 = 1.0/42 = .02$
k_7 Plant Respiration	$J_7 = k_7P$ $k_7 = 6.8/62 = .11$
k_{10} Nitrogen Export	$J_{10} = k_{10}N$ Assume bay flushes once per day $k_{10} = 1.0$
k_{11} Nitrogen Recycling	$J_{11} = k_{11}(k_{19}D + k_{16}B)$ $k_{11} = .21/(.22(13) + .0039(15)$ $k_{11} = .073$
k_{14} Nekton Respiration	$J_{14} = k_{14}F_3$ Summer: $k_{14} = .35/(4.2)^3 = .005$ Winter: $k_{14} = .05/(1.6)^3 = .012$ (mean k_{14} = .008)
k_{15} Nektonic Predation on Benthics	$J_{15} = k_{15}B\cdot F$ Summer: $k_{15} = .27/(13.7)(4.1) = .0048$ Winter: $k_{15} = 1.0/(10.4)(1.1) = .0087$ (mean k_{15} = .068)
k_{16} Benthic Respiration	$J_{16} = k_{16}B^2$ Summer: $k_{16} = 0.65/(13.7)^2 = .0034$ Winter: $k_{16} = 0.48/(10.4)^2 = .0044$ (mean k_{16} = .0039)
k_{17} Benthic Detritivory	$J_{17} = k_{17}D(k_BB + F)$ Summer: $k_{17} = 0.9/17(.33(13.7) + 4.1) = .0061$ Winter: $k_{17} = 0.4/13.5(.33(10.4) + 1.1) = .0061$
k_{19} Detrital Respiration	$J_{19} = k_{19}D$ Summer: $k_{19} = 5.2/17 - 0.30$ Winter: $k_{19} = 2/13.5 = 0.15$
k_{21} Detrital Export	$J_{21} = k_{21}D$ $k_{21} = 7.0/16$ $= 0.43$

Table F3. (Continued)

Coefficient	Calculation
k_{22} Benthic Death Rate	$J_{22} = k_{22}B$ Summer: $k_{22} = .78/13.7 = .056$ Winter: $k_{22} = .21/10.4 = .020$ (mean $k_{22} = 0.038$)
k_{23} Nekton's Death Rate	$J_{23} = k_{23}F$ Summer: $k_{23} = .125/4.1 = .030$ Winter: $k_{23} = .03/1.1 = .028$
k_{24} Nekton's Emigration	$J_{24} = k_{24}F$ when $T > 20°C$, $k_{24} = .005/1 = .005$ otherwise, $k_{24} = 0$
k_{31} Nekton's Detritivory	$J_{31} = k_{31}D \cdot F$ $k_{31} = .10/(12)(3.5) = .0024$

Table F4. Computer program of model used to simulate estuarine ecosystem at Crystal River, Florida.

```
PAGE 2        CRYSTAL RIVER ESTUARY MODEL    2/08/77 21:48

              * CRYSTAL RIVER ESTUARY MODEL
              NOTE STATE VARIABLES
              L PRD.K=PRD.J+DT*(J8.JK+J1.JK-J3.JK-J4.JK-J5.JK-J6.JK-J7.JK)
              L NTR.K=NTR.J+DT*(J9.JK+J11.JK-J2.JK-J10.JK)
              L BEN.K=BEN.J+DT*(J17.JK+J5.JK-J15.JK-J16.JK-J22.JK)
              L NEK.K=NEK.J+DT*(J4.JK+J15.JK+J13.JK-J12.JK-J14.JK-J23.JK+J31.JK)
              L DET.K=DET.J+DT*(J20.JK+J6.JK-J21.JK-J17.JK-J19.JK+J22.JK+J23.JK
              X     -J31.JK)
              NOTE RATES
              R J1.KL=K1*(AUX1.K*AUX9.K*AUX10.K)*(AUX11.K/(1+KP*AUX11.K))
              R J2.KL=K2*K1*(AUX1.K*AUX9.K*AUX10.K)*(AUX11.K/(1+KP*AUX11.K))
              R J3.KL=K3*PRD.K
              R J4.KL=K4*PRD.K*NEK.K
              R J5.KL=K5*PRD.K*(K8*BEN.K+NEK.K)
              R J6.KL=K6*PRD.K
              R J7.KL=K7*PRD.K
              R J8.KL=KX*AUX3.K
              R J9.KL=KX*AUX4.K
              R J10.KL=K10*NTR.K
              R J11.KL=K11*(K19*DET.K+K16*BEN.K)
              R J12.KL=AUX5.K
              R J13.KL=AUX6.K
              R J14.KL=K14*NEK.K*NEK.K*NEK.K
              R J15.KL=K15*BEN.K*NEK.K
              R J16.KL=K16*BEN.K*BEN.K
              R J17.KL=K17*DET.K*(K8*BEN.K+NEK.K)
              R J19.KL=K19*DET.K
              R J20.KL=KX*AUX7.K
              R J21.KL=K21*DET.K
              R J22.KL=K22*BEN.K
              R J23.KL=K23*NEK.K
              R J31.KL=K31*DET.K*NEK.K
              NOTE AUXILIARIES
              A AUX1.K=TABLE(TABI,TIME.K,0,720,30)
              A AUX3.K=TABLE(TABP,TIME.K,0,720,30)
              A AUX4.K=TABLE(TABN,TIME.K,0,720,30)
              A AUX5.K=FIFGE(0,K24*NEK.K,AUX8.K,20)
              A AUX6.K=FIFGE(0,.03,20,AUX8.K)
              A AUX7.K=TABLE(TABO,TIME.K,0,720,30.)
              A AUX8.K=TABLE(TABT,TIME.K,0,720,30.)
              A AUX9.K=1-KD*AUX12.K
              A AUX10.K=AUX8.K*(1-KT*(AUX8.K-10))
              A AUX11.K=PRD.K*NTR.K
              A AUX12.K=TABLE(TABS,TIME.K,0,720,30)
              NOTE CONSTANTS
              C KD=.0833
              C KT=.0286
              C K8=.33
              C KP=.05
              C KX=.75
              C K1=.020
              C K2=.075
              C K3=.0063
              C K4=.00067
              C K5=.002
              C K6=.02
              C K7=.11
              C K10=.75
```

Table F4. (Continued)

```
PAGE 3       CRYSTAL RIVER ESTUARY MODEL     2/08/77 21:48

          C K11=.073
          C K14=.008
          C K15=.0068
          C K16=.0039
          C K17=.0061
          C K19=.22
          C K21=.312
          C K22=.038
          C K23=.029
          C K24=.005
          C K31=.0024
          NOTE INITIAL CONDITIONS
          N PRO=60.0
          N DET=18.0
          N NTR=0.65
          N BEN=15.6
          N NEK=3.0
          NOTE TABLES
          T TABI=5.5/6.0/5.6/5.2/4.8/4.2/3.8/3.2/3.0/3.2/3.6/4.4/
          X      5.5/6.0/5.6/5.2/4.8/4.2/3.8/3.2/3.0/3.2/3.6/4.4/5.5
          T TABT=20.5/25.5/29.0/30.0/31.0/28.5/23.0/18.5/16.5/12.0/12.5/16.5/
          X      20.5/25.5/29.0/30.0/31.0/28.5/23.0/18.5/16.5/12.0/12.5/16.5/20.5
          T TABP=.50/.41/.22/.26/.45/.20/.19/.17/.08/.14/.26/.20/
          X      .50/.41/.22/.26/.45/.20/.19/.17/.08/.14/.26/.20/.50
          T TABD=7.5/8.0/5.0/4.5/6.5/7.5/8.0/6.50/3.0/3.5/6.5/5.5/
          X      7.5/8.0/5.0/4.5/6.5/7.5/8.0/6.50/3.0/3.5/6.5/5.5/7.5
          T TABN=0.62/0.65/0.88/1.00/1.05/0.44/0.31/0.21/0.67/0.23/0.32/0.54/
          X      0.62/0.65/0.88/1.00/1.05/0.44/0.31/0.21/0.67/0.23/0.32/0.54/0.62
          T TABS=2.8/3.2/5.5/5.3/4.5/3.7/3.8/3.9/3.6/3.3/3.0/2.8/
          X      2.8/3.2/5.5/5.3/4.5/3.7/3.8/3.9/3.6/3.3/3.0/2.8/2.8
          NOTE CONTROL
          PLOT PRO=P/J1=J/NTR=N
          PLOT BEN=B/NEK=F/DET=D
          SPEC DT=0.50/LENGTH=720/PLTPER=6.0
```

APPENDIX G

Detailed tables of data used for calculating energy qualities of estuarine animals.

Table G1. Partial feeding coefficients calculated for food web consumers (see Table G2 for example calculation for explanation).

Species	Grazing Chain				Detritus Chain			
	Herbivore	1° Carniv.	2° Carniv.	3° Carniv.	Detritivore	1° Carniv.	2° Carniv.	3° Carniv.
Zooplankton, primarily *Acartia tonsa*	0.250	---	---	---	0.750	---	---	---
Benthic micro-invertebrates, primarily polychaetes	---	---	---	---	1.000	---	---	---
Benthic macro-invertebrates, primarily *Uca pugnax*	---	---	---	---	1.000	---	---	---
Callinectes sapidus	0.040	0.070	---	---	0.200	0.690	---	---
Charcharhinus limbutus	---	0.250	---	---	---	0.750	---	---
Dasyatis sabina	---	0.044	0.071	0.006	---	0.157	0.679	0.044
Anchoa hepsetus	---	0.145	---	---	0.330	0.525	---	---
A. mitchilli	---	0.145	---	---	0.330	0.525	---	---

Table G1. (Continued)

Species	Grazing Chain				Detritus Chain			
	Herbivore	1° Carniv.	2° Carniv.	3° Carniv.	Detritivore	1° Carniv.	2° Carniv.	3° Carniv.
Strongylura sp., marina and notata	---	0.021	0.098	0.004	---	0.253	0.605	0.021
Cyprinodon variegutus	0.320	---	---	---	0.570	0.110	---	---
Floridichthys carpio	0.170	0.030	---	---	0.380	0.420	---	---
Fundulus grandis	---	0.034	0.058	---	---	0.481	0.433	---
Fundulus similis	---	---	---	---	1.00	---	---	---
Menidia beryllina	---	0.095	---	---	0.063	0.842	---	---
Eucinostamus argenteus	---	0.125	---	---	0.140	0.735	---	---
E. gula	---	0.098	---	---	0.120	0.783	---	---
Archosargus prohutocephulus	0.500	---	---	---	0.500	---	---	---
Lagodon rhomboides	---	0.02	0.079	0.001	---	0.415	0.467	0.005

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Table G1. (Continued)

Species	Grazing Chain				Detritus Chain			
	Herbivore	1° Carniv.	2° Carniv.	3° Carniv.	Detritivore	1° Carniv.	2° Carniv.	3° Carniv.
Mugil spp.	0.250	---	---	---	0.750	---	---	---
Paralichthys albigutta	---	---	0.092	0.023	---	0.131	0.620	0.135

Table G2. Example calculations for apportioning organism stocks and flows into trophic function categories, using second level detritus branch of control marsh as illustrative case.

Predator Species	Partial Feeding Coefficient, A_{i2D}	Value Apportioned to Detritus Branch, Second Level				
		Biomass[a]	Consumption[b]	Respiration[b]	Prod.[b]	Feces[b]
Fundulus grandis	(1.00 *Uca pugnax*)(0.407) + (0.063 *M. beryllina*)(0.406) + (0.33 *A. mitchilli*)(0.076) + (0.14 *E. argenteus*)(0.056) + (0.38 *F. carpio*)(0.014) + (0.75 *Mugil* sp.)(0.012) + (0.57 *C. variegatus*)(0.002) = 0.481	75.04	3.16	1.78	0.75	0.63
Lagodon rhomboides	(0.33 *A. mitchilli*)(0.362) + (0.063) *M. beryllina*)(0.272) + (1.00 *U. pugnax*)(0.258) + (0.38 *F. carpio*)(0.047) + (0.14 *E. argenteus*)(0.004) + (0.57 *C. variegatus*)(0.003) = 0.415	22.41	0.85	0.48	0.17	0.20
Strongylura sp., *marius* and *notata*	(0.33 *A. mitchilli*)(0.399) + (0.063 *M. beryllina*)(0.397) + (1.00 *U. pugnax*)(0.077) + (0.75 *Mugil* sp.)(0.022) + (0.38 *F. carpio*)(0.002) = 0.253	11.64	0.40	0.23	0.08	0.09
Paralichthys albigutta	(0.14 *E. argenteus*)(0.327) + (0.33 *A. mitchilli*)(0.190) + (0.063 *M. beryllina*)(0.182) + (1.00 *U. pugnax*)(0.011) = 0.131	0.34	0.01	0.01	7.01	7.01
Dasyatis sabina	(0.063 *M. berryllina*)(0.704) + (0.75) *Mugil* sp.)(0.115) + (0.57 *C. variegatus*)(0.035) + (0.38 *F. carpio*)(0.017) = 0.157	6.91	0.11	0.07	0.02	0.02

Table G2. (Continued)

Predator Species	Partial Feeding Coefficient, A_{i2D}	Value Apportioned to Detritus Branch, Second Level				
		Biomass[a]	Consumption[b]	Respiration[b]	Prod.[b]	Feces[b]
Eucinostomus aryenteus	(1.00 benthic inv.)(0.360) + (0.75 zooplankton)(0.50) = 0.735	60.27	4.39	2.16	1.35	0.88
E. gulu	(1.00 benthic inv.)(0.490) + (0.75 zooplankton)(0.39) = 0.783	1.57	0.10	0.05	0.03	0.02
Anchoa mitchilli	(0.75 zooplankton)(0.58) + (1.00 benthic inv.)(0.09) = 0.525	7.88	0.58	0.38	0.08	0.12
A. hepsetus	(0.75 zooplankton)(0.58) + (0.00 benthic inv.) (0.09) = 0.525	2.10	0.09	0.06	0.01	0.02
Menidia beryllina	(1.00 benthic inv.)(0.33) + (0.75 zooplankton)(0.38) = 0.842	207.13	12.68	8.12	2.02	2.54
Floridichthys cuspio	(1.00 benthic inv.)(0.33) + (0.75 zooplankton)(0.12) = 0.420	11.34	0.61	0.37	0.12	0.12
Callinectes sapidus	(1.00 benthic inv.)(0.568) + (0.629 Aug "P" valve at 1st level (0.194) = 0.690	26.22	1.10	0.66	0.22	0.22
Fundulus similis	(1.00 benthic inv.)(1.00) = 1.000	121.00	5.29	2.87	1.36	1.06
Cyprinodon variegatus	(1.00 benthic inv.)(0.11) = 0.110	1.76	0.10	0.06	0.02	0.02

Table G2. (Continued)

Predator Species	Partial Feeding Coefficient, A_{i2D}		Value Apportioned to Detritus Branch, Second Level				
			Biomass[a]	Consumption[b]	Respiration[b]	Prod.[b]	Feces[b]
Archosargus prohatocephalus	(1.00 benthic inv.)(0.50)	= 0.500	6.70	0.25	0.12	0.08	0.05
Carcharhinus linbutus	(0.75 *Mugil sp.*)(1.00)	= 0.750	80.20	1.84	0.57	0.90	0.37
Total			642.51	31.56	17.99	7.21	6.36

[a] mg organic matter/m^2.

[b] mg organic matter/m^2-day.

BIOGRAPHICAL SKETCH

William Micahel Kemp was born May 16, 1947, in Washington, D.C. He received his bachelor degree in Civil Engineering from Georgia Institute of Technology, Atlanta in 1969. In the fall of that year he began graduate studies at Georgia Institute of Technology with a U.S. Public Health Service traineeship. He received his M.S. in Sanitary Engineering and Microbiology in December, 1970. He was employed for almost two years as an environmental engineer with the U.S. Environmental Protection Agency in Boston. Since the fall of 1972 he has worked toward a Ph.D. in Environmental Engineering Sciences and Systems Ecology holding graduate assistantships.

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Chester D. Kylstra

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I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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